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DEVELOP AND EVALUATE THE GAS METAL ARC WELDING/SUBMERGED ARC WELDING PROCESS FOR IMPROVED WELD PROPERTIES

FINAL REPORT

by

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GMA-SAW PROCESS FOR STELFORM PLATE-END WELDING

Project Report
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Purpose

The Stelform plate-end welding operation performs unacceptably in the manufacture of thick line pipe (>0.650in). The welding process stability breaks down as plate thickness, or heat input increases. This results in weld defect frequencies that are too high and the intermittent occurrence of solidification cracking at the joint ends. A new plate-end welding process is needed to manufacture the full thickness range of Stelform line pipe.

A recently-developed but not commercialized process, Gas Metal Arc-Submerged Arc Welding (GMA-SAW), is considered the best candidate. Two companies, NKK and Sumitomo, were willing to sell their technological expertise but they will not guarantee that it would improve plate-end welding. Consequently, we must establish the viability and applicability of GMA-SAW to Stelform plate-end welding.

Scope

A literature search from 1970 to 1983 and searches of Derwent's patent data base from 1973 onwards were performed. A computer model to predict GMA-SAW welding procedures was developed. Experimental stations for high current gas metal arc welding (GMAW) and GMA-SAW welding trials were constructed at the Welding Institute of Canada's Oakville Laboratories and at R&D's Welding Laboratory, Welland Tube Works, respectively.

We investigated GMAW process equipment, materials, procedures, and weld characteristics, including those of preliminary GMA-SAW welds in 0.864in WT HSLA skelp, from January 1984 to July 1986.

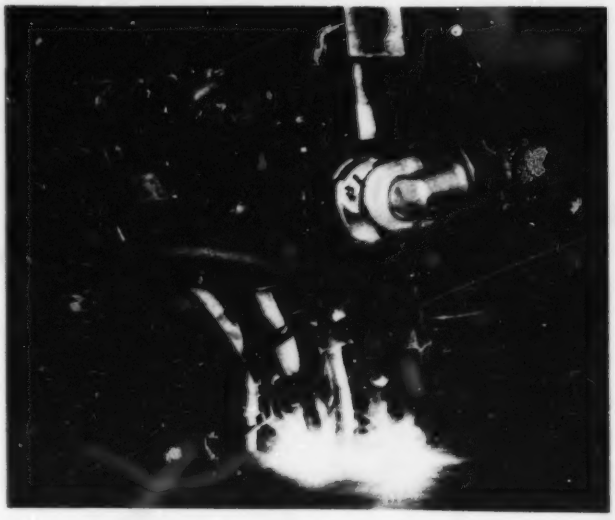
Conclusions

GMA-SAW can be applied to plate-end welding for thick skelp in the Stelform line pipe manufacture. The process:

- operates stably with single or multiple electrode gas metal arc welding in high current regimes (450 to 600 A) with good weld quality tolerances to arc current (±30 A), voltage (±3 V), and joint fit-up gap (up to 0.090in) variations.
- decreases SAW heat input for 0.864in WT by 15 to 25 percent (while achieving 85 ±5 percent penetration), which improves bead shape (d/w <1.0) and reduces sensitivity to solidification cracking.
- produces weld metal and HAZ fracture toughness at least equivalent to the present two-wire SAW process with potential for improvement as the consumables and procedures are refined.

Action

Stelpipe will design and construct a mill prototype GMA-SAW station for testing in the Stelform mill.



Laboratory 2-wire GMA-2-wire SAW (2GMA-2SAW) Welding

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INTRODUCTION

Submerged arc welding (SAW) is the traditional method used by heavy fabrication industries (e.g. shipbuilding, offshore platform construction and line pipe manufacture) for joining steel. The process combines high yield and productivity with the ability to meet metallurgical specifications for joining a wide range of steel grades under varied fabricating restrictions. Forty years of continuous research into methods, equipment and materials has refined SAW into an excellent fabricating technique.

Two trends in fabrication threaten the viability of presently-constituted SAW technology. Customers are fabricating heavier sections and they need higher weld metal and heat-affected zone (HAZ) fracture toughness.

SAW productivity depends on high rates of arc energy consumption (heat input) to achieve high deposition rates (that is, low joint completion times and labor costs). However, high heat inputs and slow weld cooling rates produce inferior microstructures and weld toughness. New welding methods involving SAW technology are required.

The conflicting requirements for productivity and improved mechanical properties can be overcome by dividing the weld deposit into two or more distinct beads that are produced simultaneously. The GMA-SAW process can achieve achieve this configuration. One or more GMAW beads is/are deposited as the root pass(es) followed by an SAW bead to fill and cap the joint in a single operation.

Most developments, prior to 1984, involving deposition of two beads in a single pass were patented and published by four Japanese pipemakers.

Kobe originated the GMA-SAW process concept and published IIW documents on the technology[1,2]. In 1960, NKK patented (Canadian Patent 1 144 092) a multi-electrode high current GMAW system for UOE seams. They also patented a GMA-SAW process as did Sumitomo and Nippon Steel (Table I).

Table I: GMA-SAW Patents

Company	Patent			GMAW Component		Welding Application
	Year	Numbers	Country	Electrode Diameter (mm)	Current (A)	
Sumitomo	1979	724528/40	Japan	3.2 - 4.8	600 - 1100	General
Nippon	1980	1125383	Canada	0.8 - 2.4	350 - 1050	UOE seam
NKK	1981	1105568	Canada	3 - 8	600 - 2000	Spiral seam

Each of these GMA-SAW process patents involve unique operating problems and proprietary welding equipment.

Large diameter pipe is manufactured using multi-electrode (two to five) SAW and assembly line methods, which restrict seam welding to two passes - one pass from each surface of the joint. Virtually all spiral pipe mills weld with relatively balanced heat inputs. The second pass (from the pipe OD) heat input is 10 to 15 percent higher than the first to ensure complete joint line fusion by overlapping the bead roots by 15 to 20 percent.

The Stelform pipemaking process provides a unique exception. Since the process uses plate rather than coiled skelp as feedstock, the plates must be joined end-to-end prior to spiral pipe forming. To maintain high weld quality levels, the plates are also welded in two passes (one from each surface of the joint); however, the heat inputs are highly imbalanced. The first pass from the top surface of the plate (plate-end weld) uses high heat input. It penetrates the joint more than 70 percent so that the weld withstands the bending forces in spiral pipe forming without tearing apart. The joint is completed from the other side (now the pipe OD) with a low heat input pass, "OD completion weld", to assure a 15 to 20 percent overlap of the bead roots. The longitudinal plate edges form the spiral seam of the pipe and are welded with two passes using balanced heat inputs like other spiral pipe mills.

Stelpipe experienced operating and quality problems in the plate-end welding operation. The high heat input and deep joint penetration required to weld the thick plate ($\geq$0.650in) led to arc instability, producing toe defects, joint burn-through, and centerline solidification cracking at the joint ends. The steps taken to remedy these problems met with little or no success. The arc instability was not improved by upgrading the welding control system. Joint burn-through frequency was reduced by lowering the penetration specification from 85 to 75 percent, but it was at the expense of increasing the risk of joint failure in spiral forming. Solidification cracking frequency was decreased by reducing the bead depth/width ratio and burn-through frequency, but it was not eliminated.

We approached the British Welding Institute, NKK, Sumitomo, and Nippon Steel about solving the plate-end welding problems in 1983. NKK was willing to assist us, but Stelpipe could not justify the expense without a firm market for thick Stelform line pipe. Stelpipe needs to confirm the viability of GMA-SAW and the benefits of its application to plate-end welding with minimum financial risk. The Department of Supply and Services (DSS) and CANMET provided the funding to investigate GMA-SAW. A major portion of the technical work was subcontracted to the Welding Institute of Canada (WIC), which included technical literature and patent searches[3,4], computer modeling welding procedures and confirmation of GMAW high current operability[5].

WIC constructed an experimental station for high current GMAW trials at the Oakville Laboratory (Appendix 1). It was used to evaluate welding equipment and consumables and then locate stable high current welding regimes (Tables II and III)[6].

Table II: Primary GMAW Parameters and Levels Studied

Variable	Level
Shielding Gas:	
• Composition	CO_2, CO_2/A, A, A/O_2
• Delivery Apparatus	cup, side tube
• Flow Rate (scfh)	70 to 95
Electrode Type:	
• Vendor/Trade Name	Linde 65, Liquid Carbonic RD21
• Diameter (in)	0.062, 0.096, 0.125
Electrode Configuration:	
• Setup	1, 2, twin
• Spacing (in)	0.75, 5.5
• Angles (°)	90
• Stand-off (in)	0.75, 1.0, 1.5
Power/Transmission:	
• Source	Lincoln CPMG, CDMG; ESAB LAD 1000
• Ground	toward, away from
• Busbar	Linde 29N19, ESAB, twin
Workpiece:	
• Material/Wt (in)	HSLA 0.835 and 0.920in; structural plate 1.000in;
• Test Configuration	bead-on-plate; bars machined and tack welded together forming edge-prepared butt joints

Table III: Secondary GMAW Parameters and Levels Studied

Variable	Level
Joint Configuration:	
• Gap (in)	0 to 0.096
• Bevel Angle (°)	40 ±2, 50 ±2
• Land Thickness (in)	0.250 to 0.350
Heat Input:	
• Current (A)	350 to 750
• Voltage (V)	26 to 38
• Travel Speed (in/min)	20 to 35

We built a second experimental station for GMA-SAW in the R&D Welding Laboratory (Appendix 1). It was used to define the tolerances of GMA weld quality to variations in heat input and joint fit-up and produce preliminary GMA-SAW welds in HSLA plate for mechanical property assessment.

GMA-SAW Operating Characteristics

The main problem in the GMA-SAW investigation was to determine which GMAW operating conditions deposit a high-quality root pass in a reliable and consistent manner with equipment that operates under demanding conditions.

We assumed that no new developments in the SAW process component are required; that is, conventional equipment for filler pass deposition could be modified to meet the GMA-SAW requirements.

The technical uncertainties associated with the SAW component lie in its interaction with the GMAW component. Topics, such as separation distance, plus the root and filler pass heat inputs, require study to optimize the weld deposit physical and mechanical properties.

Essentially, the GMAW component must operate outside its normal range* and, therefore, considerable development work was needed to confirm the process operability. The key characteristics of arc welding operability are:

- arc stability,
- metal transfer,
- fusion characteristics,
- electrode melting and deposition rates, and
- weld quality.

We defined the process operating tolerances and working lobes in terms of these characteristics and assessed the viability of the GMAW conditions for commercial application.

1. GMAW Arc Stability

Arc stability, defined as the uniformity of arc length for direct current welding (voltage), determines the consistency and uniformity of the weld deposit and welding operation. For a given welding procedure and consumable selection, it is normally a function of the electrical arc control equipment (i.e. power supply and wire feed system). The GMA-SAW process operates stably at high current levels with single or multiple electrode GMAW provided suitable equipment is used. GMAW arc stability does not present a barrier to commercially applying GMA-SAW.

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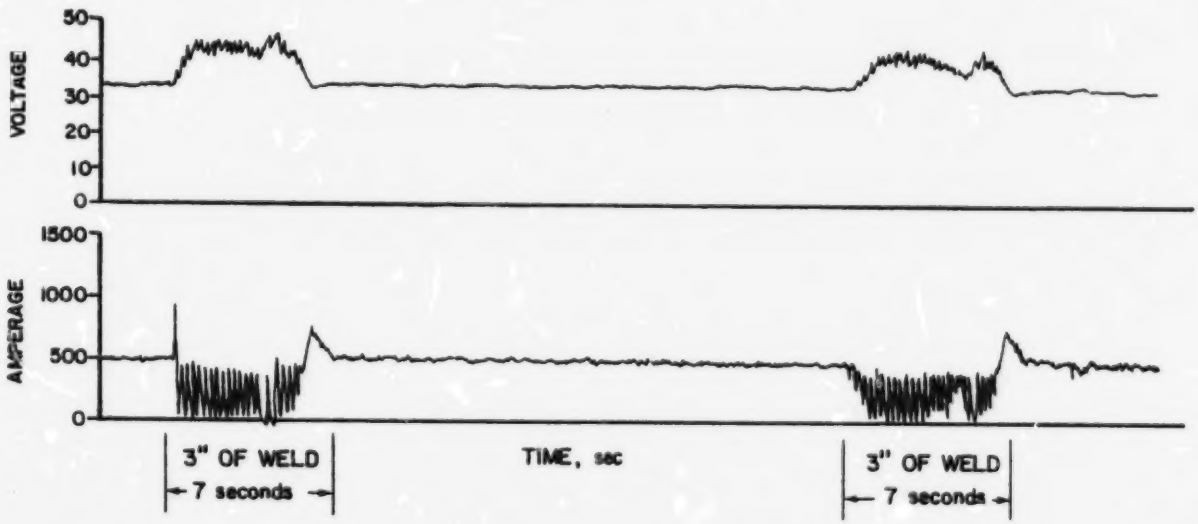
* electrode diameters of 0.032 and 0.045in and arc currents ranging between 150 and 300 A.

Good arc stability is achieved only using certain types of commercial welding equipment; that is:

- ESAB constant potential (CP) LAD 1000 rectifier power supply and A6 wire feed control (Table I A1),
- Lincoln constant current (CC) motor-generator and LAF-3 wire feed control (Table II A1), and
- Linde single and twin bus bar assemblies (Table II A1).

A Lincoln constant potential motor-generator and LAF-3 wire feed control performed well in bead-on-plate tests but not in welding beveled joints. Intermittent arc instability occurred (Figure 1) and lasted a matter of seconds before uniform arc length was reestablished.

Figure 1: Intermittent GMAW Arc Instability



The instability resulted in excessive spatter levels. The unacceptable performance was not due to faulty equipment and may be a characteristic of the power source under these operating conditions.

Welding tests with ESAB twin-wire and single wire bus bar assemblies were unsuccessful. These bus bars overheated due to the high welding currents, causing expansion of the contact tip, poor current transfer to the electrode wire and breakdown of arc stability. The Linde bus bar assemblies are better designed, using larger components and tips with more surface contact with the electrode wire to prevent overheating.

In two-wire tandem GMAW tests, where the electrodes were separated by 5.5in, there were no adverse effects on the arc stability of the lead and trail electrodes. Welding was performed toward the ground point for both electrodes. We did not observe arc instability or arc blow with this configuration.

2. GMAW Metal Transfer

The GMA-SAW process operates stably using high current GMAW, when the procedures promote the "buried spray" mode of metal transfer.

Several modes of molten metal transfer from the electrode tip to the weld pool exist for GMAW. The transfer mechanism depends on the electrode diameter, welding current and welding voltage, or arc length (arc length is approximately proportional to the voltage measured between the electrode and workpiece). Welding current essentially controls electrode melting rate for a given diameter and electrode extension (beyond the contact tip), higher current melts the electrode faster.

Welding voltage sets the transfer mechanism for a given current level. Under low current and voltage conditions metal is transferred by actually bridging the gap between the electrode tip and workpiece, which is known as "short circuit" or "dip" transfer. Under higher voltage levels for the same current level, the transfer occurs as drops that are larger than the electrode diameter, hence the term "globular" transfer. By increasing current at these higher voltage levels the magnetic fields surrounding the electrode pinch smaller droplets of molten metal from the electrode tip at a high frequency producing "open spray" transfer. This transfer mechanism is most widely used for GMAW followed by short circuit transfer; globular transfer tending to be too unstable for practical application.

More recently a fourth transfer mechanism termed "buried spray" has been recognized and used. Buried spray occurs when the arc force cuts a channel in the workpiece so that at lower operating voltages (i.e. shorter arc lengths) the arc is below the workpiece surface and is not visible to the operator. Judicious selection of shielding gas stabilizes the arc and superior penetration and filler metal deposition characteristics at high currents occur compared with "open spray" transfer welding conditions. Electrode composition does not effect metal transfer.

Shielding with argon or carbon dioxide (CO_2) alone did not support stable "buried spray" metal transfer. Only mixtures of gases generated stable metal transfer with low levels of spatter. A 95/5 percent argon/oxygen gas mixture performed well, but it did not provide desirable bead shapes (to be discussed later in the report). Mixtures of 95/5 percent argon/oxygen with 30 to 80 percent CO_2 satisfied the metal transfer and bead shape requirements as did 90/10 percent CO_2/argon, and 75/25 percent CO_2/argon. The operators selected the latter argon/CO_2 mixture for "buried spray" metal transfer in the GMA-SAW development.

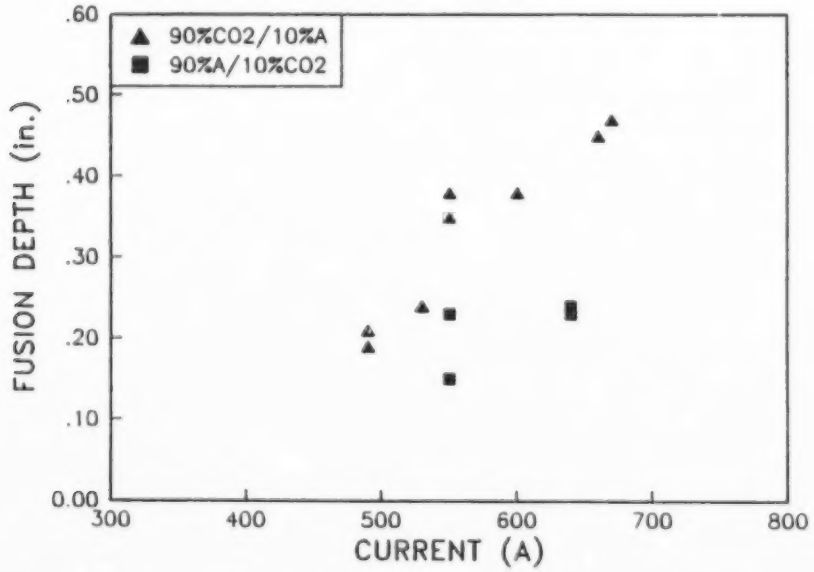
3. GMAW Fusion Characteristics

Fusion depth is a fundamental characteristic of each welding process. The depth of joint fusion achieved by a process is a key factor used in welding procedure design. The greater the joint fusion depth, the less edge preparation, electrode deposition and, therefore, fabrication cost is required in joining operations.

The joint fusion characteristics of GMAW are well-suited to plate-end welding. The GMA-SAW process permits better regulation of the joint fusion depth than the two-wire SAW process and avoids joint burn-through caused by variable fit-up gap.

In consumable electrode welding with DC power, maximum fusion depth is achieved when the electrode is positive (cathode), the voltage level is low and the current level is high. In GMAW, the shielding gas also plays a role in determining the depth of fusion. Active shielding gases, such as CO_2, promote deeper fusion by increasing the heat generated by the arc and/or concentrating the plasma forming the arc column (Figure 2).

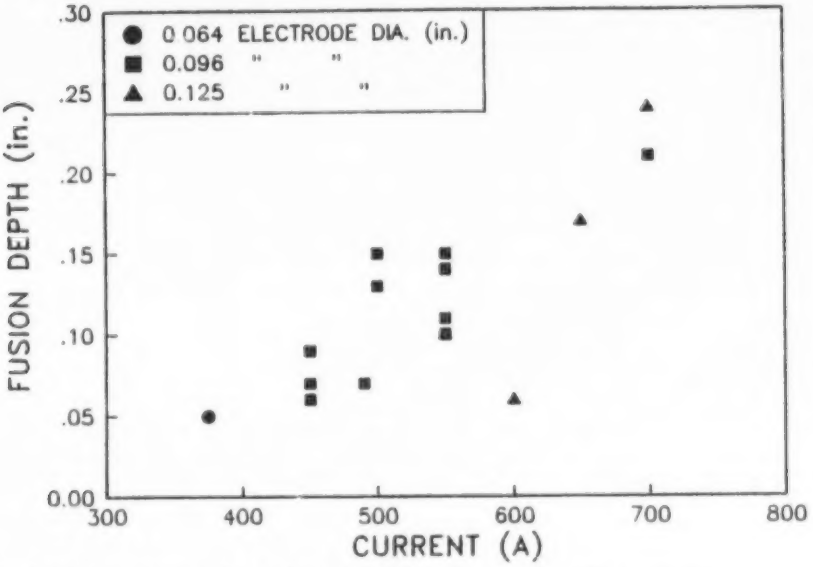
Figure 2: GMAW Arc Fusion Depth Using Argon or CO_2-rich Shielding Gas Mixtures*



* Bead-on-plate welding with 0.096in diameter electrode at 25in/min travel speed.

The conditions for deep fusion are precisely those of the operating regime for "buried spray" metal transfer. Increasing current, produces fusion below the root of the beveled joint preparation (Figure 3) regardless of electrode diameter.

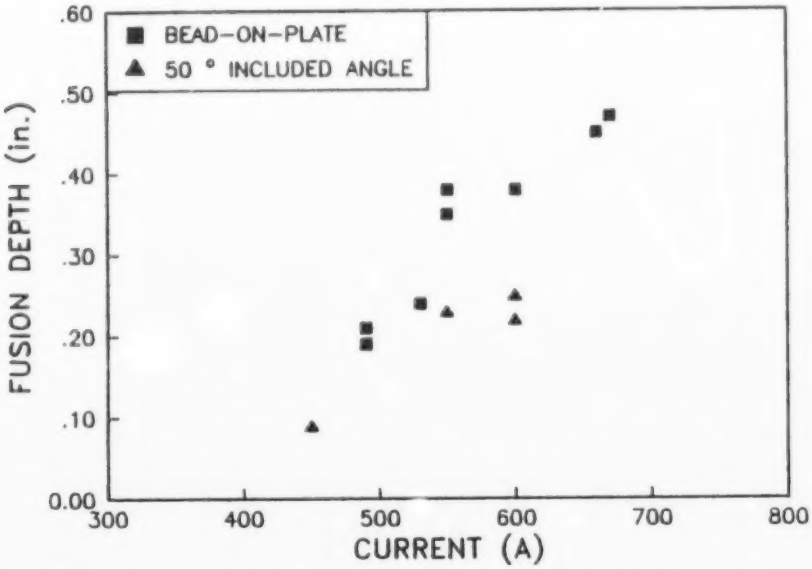
Figure 3: Influence of Current on Fusion Depth*



* Single-wire, 25in/min, 90/10 percent CO_2/Argon, 50° included angle joint preparation

However, travel speed and joint configuration also influenced fusion depth. A 30 to 50 percent reduction in fusion depth resulted when changing from bead-on-plate to welding a 50° included angle joint preparation (Figure 4).

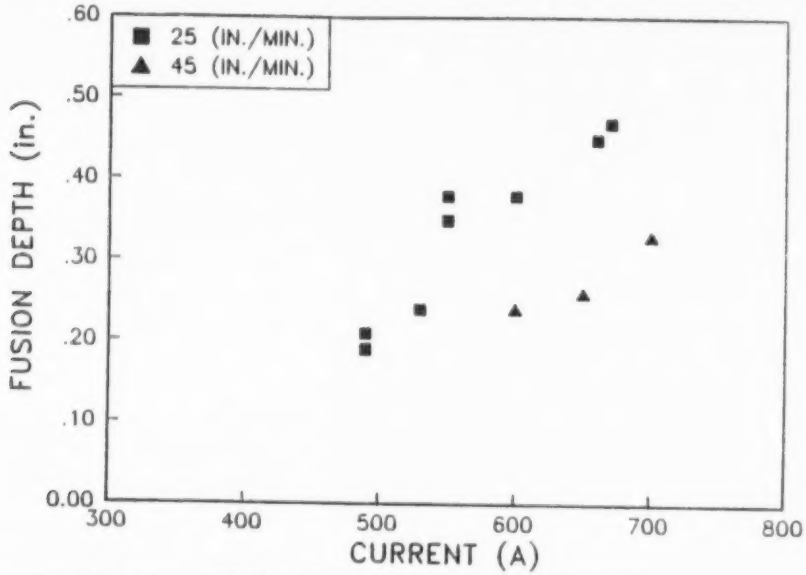
Figure 4: Influence of Joint Configuration on Fusion Depth*



* Single-wire, 25in/min, 90/10 percent CO_2/Argon

Also, a 30 percent reduction in fusion depth occurred, when we increased the travel speed from 25 to 45in/min (Figure 5).

Figure 5: Influence of Travel Speed on Fusion Depth*

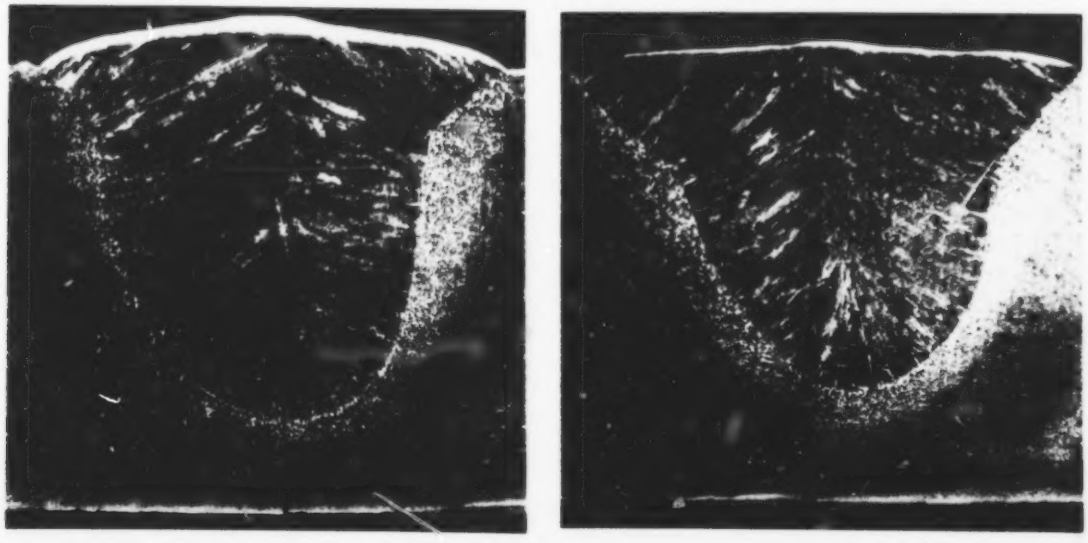


* Single-wire GMAW, 40/10 percent CO_2/Argon

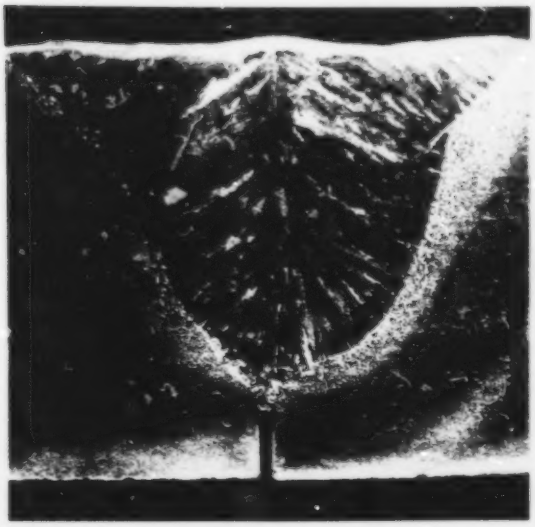
Currently, the plate-end joint for two-wire SAW is restricted to a 0.010in maximum gap, otherwise extraordinary measures (filling the gap with electrode wire) are taken prior to welding to minimize the risk of joint burn-through. The GMAW process tolerates a gap at least six times wider than the two-wire SAW process; consequently, GMA-SAW will provide uniform, controlled penetrations in plate-end welding (Figure 6).

Figure 6: GMA-SAW Joint Gap Tolerance (≈3X)

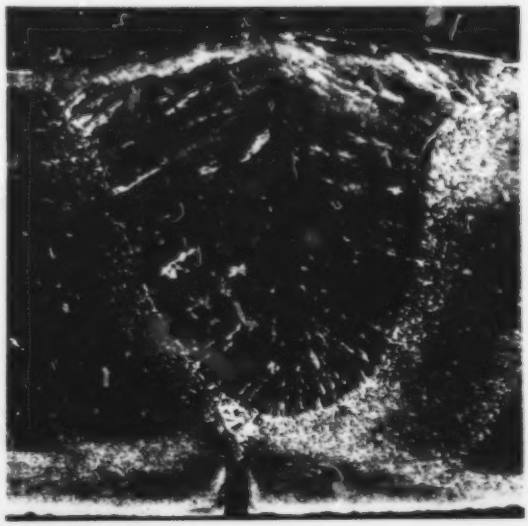
(a) 0 Gap, 77% Penetration **(b) 0.007in Gap, 75% Penetration**



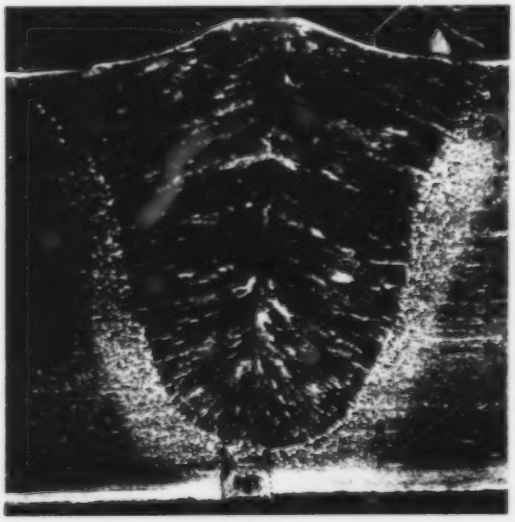
(c) 0.018in Gap, 74% Penetration



(d) 0.054in Gap, 78% Penetration



(e) 0.105in Gap, 89% Penetration



The fusion depth was relatively unaffected by joint fit-up gap in comparison to two-wire SAW.

The shape of the fusion zone is also important in welding procedure design. A narrow fusion zone does not provide acceptable tolerance to variations in seam tracking and results in variable joint fusion depth. Shielding with 95/5 percent argon/oxygen gas mixture produced a fusion zone at the weld root that was too narrow (Figure 7). Additions of CO_2 gas between 30 to 80 percent to this mixture improved the fusion zone shape (Figure 8). Similar shapes were achieved with plain CO_2/argon mixtures ranging between 95/5 and 75/25 percent, which are preferred because they are less expensive (Figure 9).

Figure 7: GMAW Bead Profile using Argon/Oxygen Shielding Gas

Figure 8: GMAW Bead Profile using Argon/Oxygen/CO_2 Shielding Gas

Figure 9: GMAW Bead Profile using Argon/CO_2 Shielding Gas

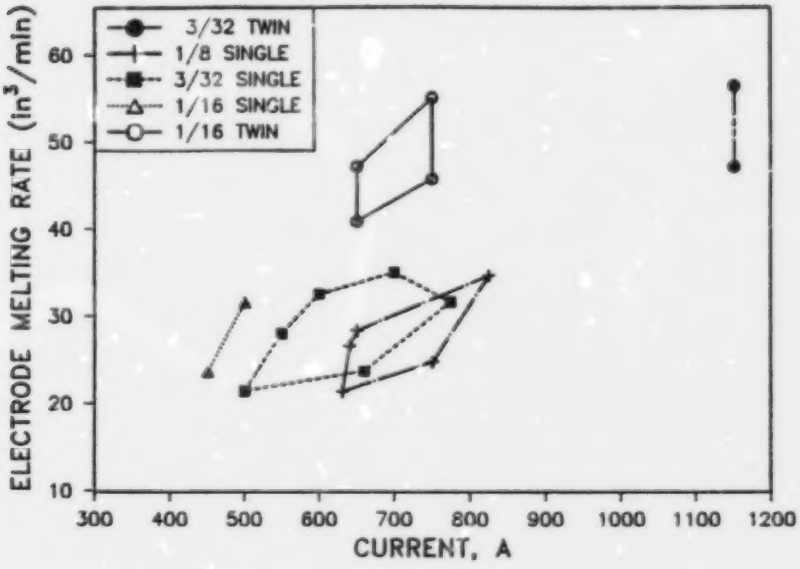
4. GMAW Electrode Melting and Deposition Rates

The amount and rate of electrode wire added or deposited to fuse the joint is a major factor determining fabrication productivity and cost. The selection of welding processes and procedures and techniques basically depends on the rate of deposition exclusive of metallurgical constraints. GMAW electrodes operate at high melting rate efficiency (lb/h) and this allows increased productivity for GMA-SAW compared to SAW. Higher productivity is a major commercial advantage of the GMA-SAW process.

Many welding processes and techniques have been developed that improve deposition rates, minimize the amount of deposition required or eliminate deposition altogether (i.e. autogeneous welding by electron beam, friction, diffusion, laser, etc). Most efforts to increase deposition involve multiple electrode wires, and recent GMAW developments are no exception[8]. For single wire GMAW the deposition rate is fixed by the electrode melting rate, which is mainly a function of current density for a given electrode diameter and extension. A fine electrode wire operated at high current provides the fastest deposition rate but not necessarily an acceptable weld.

Figure 10 summarizes deposition rates for various electrode diameters and operating current levels.

Figure 10: GMAW Electrode Melting Rate



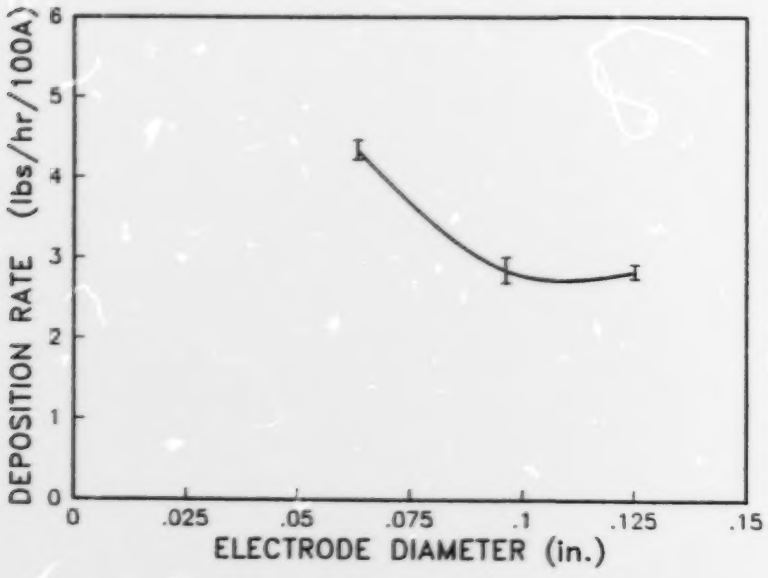
Twin 0.064in diameter electrodes provide the highest weld metal deposition rates at the lowest operating current. Table IV provides examples of current densities and measured deposition rates.

Table IV: Electrode Melting Rates

Electrode Diameter (in)	Cross Section Area (in^2)	Current (A)	Current Density (A/in^2)	Measured Deposition Rate (lb/hr/100 A)
0.063	0.00312	500	104200	4.22 - 4.46
0.096	0.00723	675	89900	2.69 - 3.02
0.125	0.0123	650	52800	2.74 - 2.92

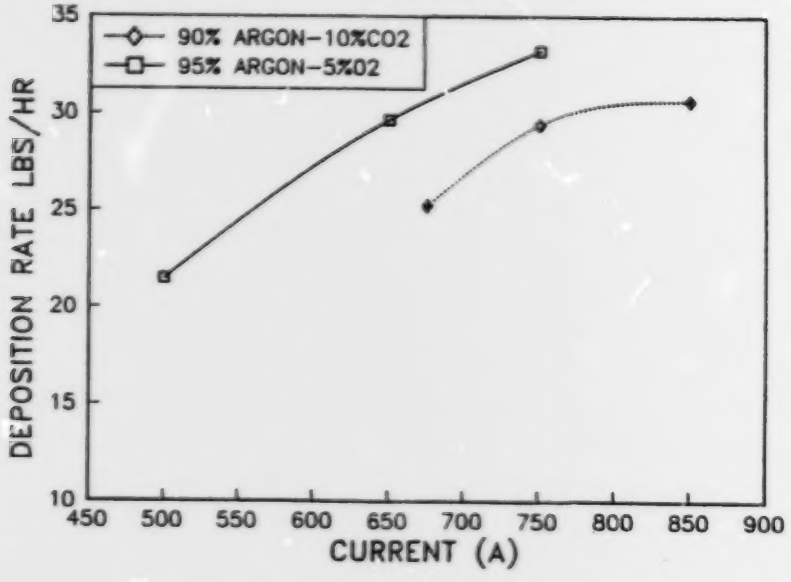
Electrode melting rate is 48 percent greater for each 100 A welding current using 1/16in versus 3/32in or 1/8in diameter wire (Figure 11).

Figure 11: GMAW Electrode Melting Effectiveness



The shielding gas composition also affects the electrode melting rate. Figure 12 shows that an argon/oxygen mixture increases the melting rate approximately 15 to 20 percent compared to an argon/CO_2 gas mixture.

Figure 12: GMAW Electrode Melting Rates for two Gas Shielding Mixtures



5. GMAW Weld Quality

Welds in large diameter line pipe undergo 100 percent NDT inspection to assure the customer that the welds meet the quality specified by the CSA Z245 standard. In fact, weld inspection is incorporated into the pipe manufacturing sequence. It includes 100 percent fluroscopic examination, 100 percent ultrasonic testing, weld end and intersection X-ray photography and visual surface inspection. Most surface and internal defects (except cracks) can be repaired if they meet the criteria set out in the standard. Defects that cannot be repaired or repaired welds that fail reinspection are cut out of the pipe and the pipe ring containing the defect(s) is scrapped. Weld defects, therefore, pose significant productivity and yield losses.

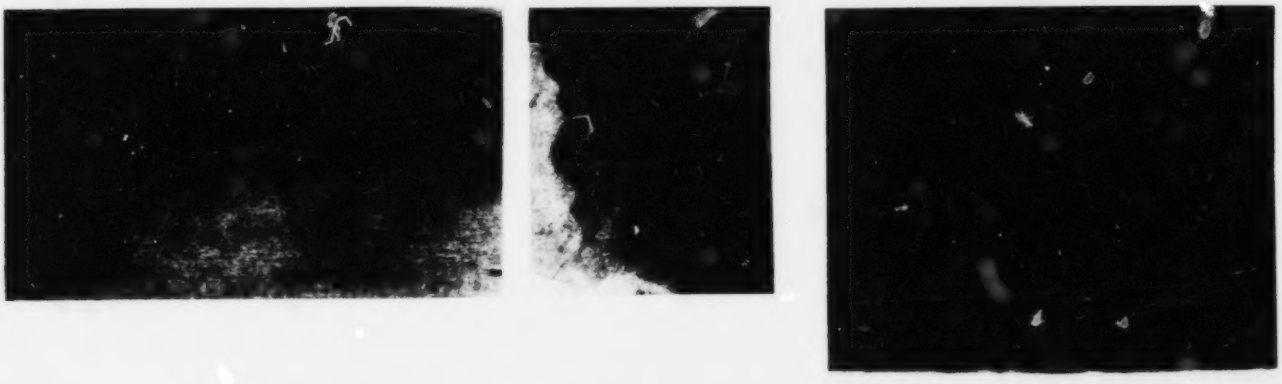
The GMAW component of GMA-SAW consistently provides acceptable weld quality in the laboratory. The welding procedure tolerances for quality welds are defined in lobes that are large enough to support commercializing GMA-SAW for plate-end welding.

The same cause and effect relationships established between GMAW parameters and quality for "normal" spray transfer operation also apply in the buried spray operating regime, viz:

- excessive current causes lack-of-fusion defects at the weld toe (Figure 13a)
- poor shielding of the weld pool produces porosity defects (Figure 13b)
- excessive heat input increases the bead depth/width aspect ratio >1.0 leading to centerline solidification cracking (Figure 13c)

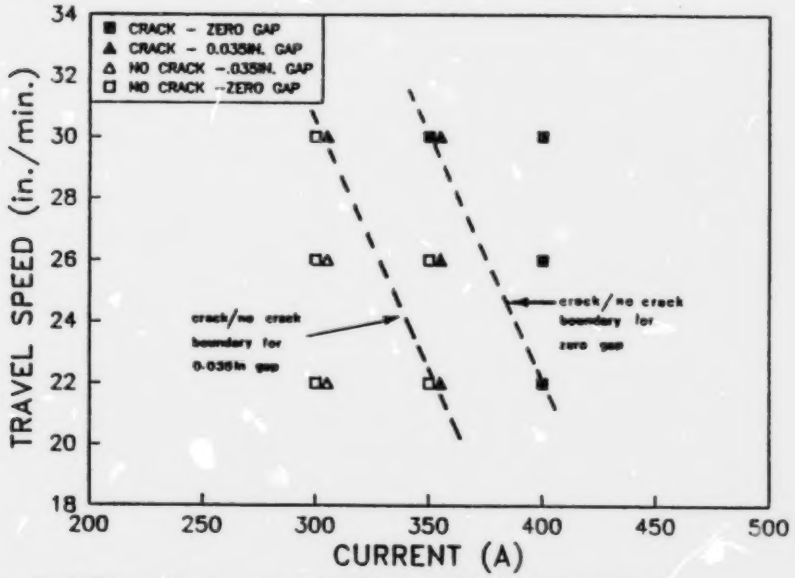
Figure 13: GMAW Defects

(a) Lack of Fusion **(b) Porosity** **(c) Solidification Crack**



We found that the occurrence of solidification cracking is a major limiting factor in GMAW procedure selection. High welding currents and travel speeds promote cracking and restrict welding with 0.096in diameter electrodes to 500 A or less. Figure 14 shows the crack free operating ranges with 0.063in diameter electrodes.

Figure 14: GMAW Solidification Cracking*


CRACK - ZERO GAP
CRACK - 0.035IN. GAP
NO CRACK -.035IN. GAP
NO CRACK -ZERO GAP
TRAVEL SPEED (in./min.)
CURRENT (A)
crack/no crack boundary for 0.036in gap
crack/no crack boundary for zero gap

* 0.063in electrode diameter; 75/25 percent CO_2/argon shielding gas; 50° included angle joint preparation, 0.67in deep.

Joint gap promotes cracking and reduces the tolerable current operating levels (see Table V A2 for details). Tandem GMAW welding can overcome the solidification cracking problem by melting and refusing any imperfections in the upper portion of the deposit of the leading electrode. Ohshita et al[10] indicates that increasing the weld carbon content to >0.14 wt is also a means of preventing solidification cracking.

Successful GMAW can be achieved by shielding the arc and weld pool from atmospheric contamination. Shielding is essential otherwise weld porosity and arc instability result. We tested two methods to direct shielding gas into the weld zone, side tube or gas "cup". The side tube proved the simplest and most effective technique (see Appendix 1).

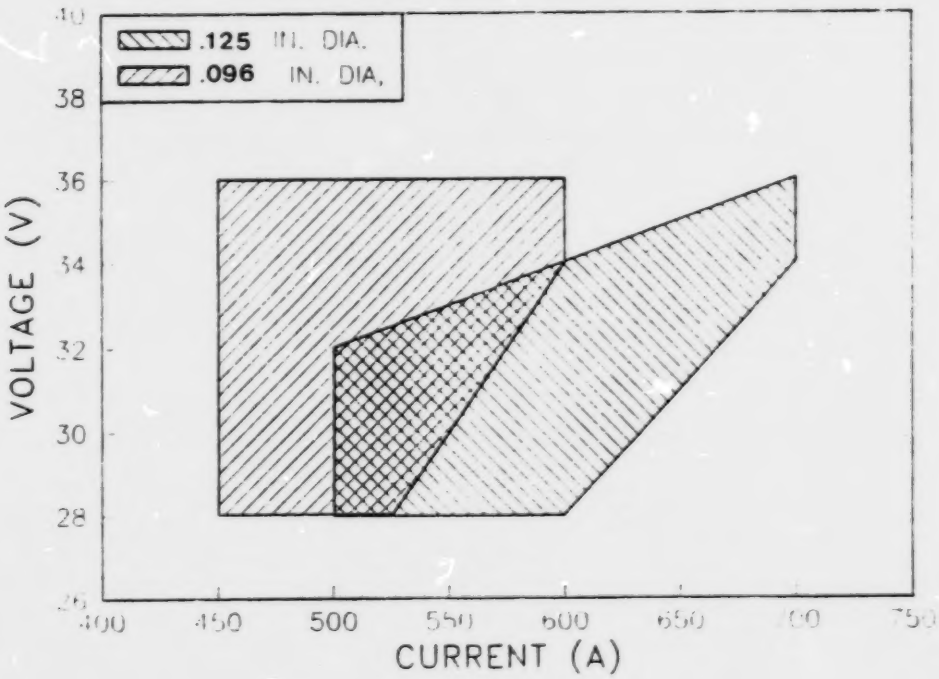
Acceptable weld quality is achieved only within clearly define setup and operating conditions. The response of high current GMAW to operating conditions is defined in tolerance lobes. The boundaries of the lobes are set by the following weld quality acceptance criteria:

- no solidification cracking

- no porosity
- no lack-of-fusion
- joint fusion depth greater than 0.10in
- no evidence of arc instability (voltage regulation <2 V)
- minimum spatter

Lobes for current and voltage variation with 0.096in versus 0.125in diameter electrodes wires using 75/25 percent CO_2 argon shielding gas show tolerances for buried spray GMAW that are acceptable for industrial application (Figure 15 and Table I A2).

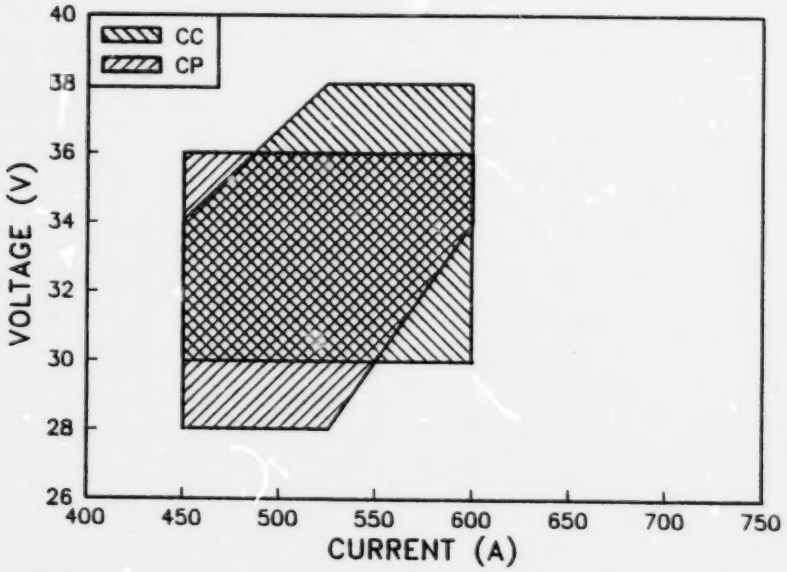
Figure 15: GMAW Operating Tolerance Lobes for 0.096in and 0.125in Diameter Electrodes



The upper current limit for 0.096in electrodes is determined by the onset of solidification cracking.

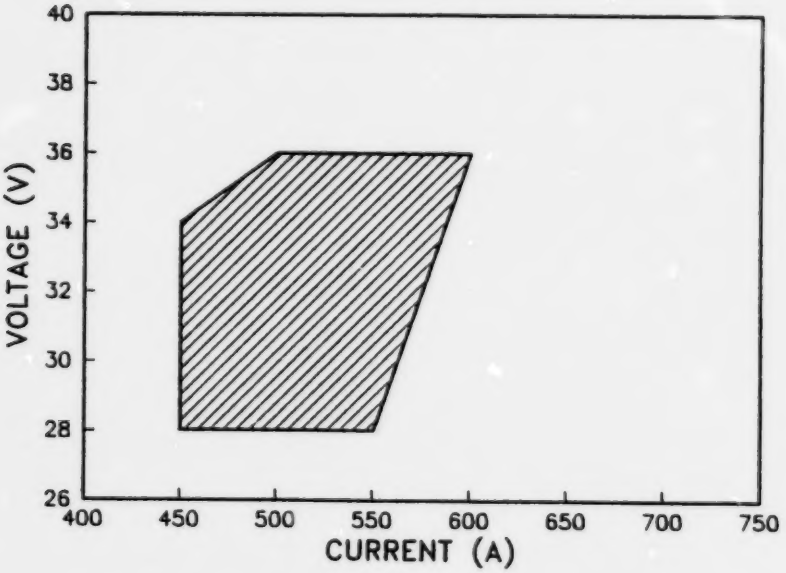
The power source design also affected GMAW operating tolerances. The current and voltage lobe for constant arc regulation extended to higher currents and/or voltages than the lobe for a constant potential regulation system (Figure 16). Welding with two-wire, tandem GMAW did not result in detectable arc interaction between the lead and trail electrodes. The lobes for the 0.096in diameter lead electrode operating under constant potential regulation were virtually the same (compare Figure 17 with Figure 16).

Figure 16: GMAW Operating Tolerance Lobes for Constant Potential and Constant Current Arc Regulation*



* 0.096in dia electrode at 25in/min travel speed

Figure 17: GMAW Operating Lobe for the Lead Arc in a Two-wire Tandem System*



* bead-on-plate welds at 525 A, 32 V, 30in/min with CP lead electrode and CC trail electrode regulation

GMA-SAW Heat Input

Heat input is the basis for welding procedure design. Researchers have related it empirically to electrode melting rate, weld penetration and weld fusion area for specific welding techniques and operating regimes. More recently, research is being performed to relate the effects of heat input (i.e. peak weld pool temperature and its duration, average weld cooling rate) to weld metal and HAZ microstructures and mechanical properties. Therefore, heat input provides the operational link between bead formation and weld metallurgy.

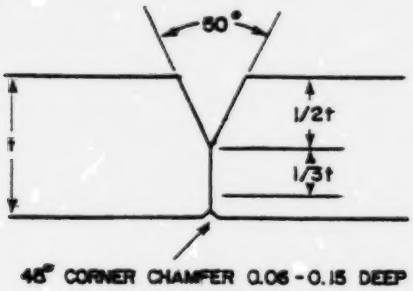
GMA-SAW reduces the plate-end weld SAW heat input but it does so at the expense of process simplicity. Two and even three-wire (or one plus twin-wire) GMAW heads will be required to weld thick plate.

Although the reduction in SAW heat input using GMA-SAW is only 20 percent, the bead shape is much improved to prevent solidification cracking. The GMAW deposit eliminates the problems of submerged arc welding the root of a narrow joint preparation with varying joint gap. The SAW bead has a lower D/t ratio (1.0 to 1.1) and a wide bead root that is preferred to increase seam tracking tolerances and resistance to solidification cracking (see Figure 4). No GMA-SAW welds exhibited solidification cracks in the SAW deposit. The process has the potential to eliminate this problem in Stelform plate-end welding.

In multi-wire SAW, the arcs form a common weld pool. Consequently, the process heat input equals the total rate of energy consumption for all the arcs. Combining the arc energies does not increase weld penetration. The penetration is determined by the lead arc because it operates at the highest arc energy (otherwise unstable interaction usually occurs between the arcs making the process unworkable). The deep penetration required by the plate-end weld is achieved by beveling the joint edges. The total penetration comprises the depth of fusion from the arc energy plus the depth of fusion from beveling and filling the edge preparation with deposited electrode metal. As the plate thickness increases so does the bevel depth to meet the penetration objective. The problem is that the joint preparation area increases exponentially with a linear increase in bevel depth. This means that very high heat input welding procedures are required to fill and cap the edge preparations to meet the 85 percent penetration objective for plate-end welds in thick plate.

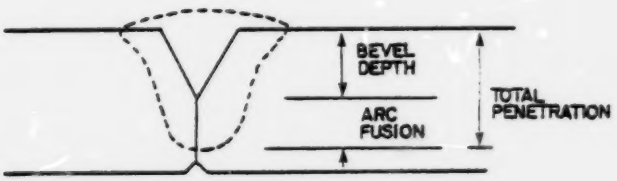
To minimize the edge preparation area, thus the heat input/deposition requirement, the bevel angle is set at 25° which is narrow by industry standards for SAW. The joint preparation is a single V, 50° included angle, approximately one-half the plate thickness deep from the top surface with a square butting "land" region one-third the thickness at the bottom of the joint (Figures 18).

Figure 18: Typical Plate-end Weld Joint Preparation



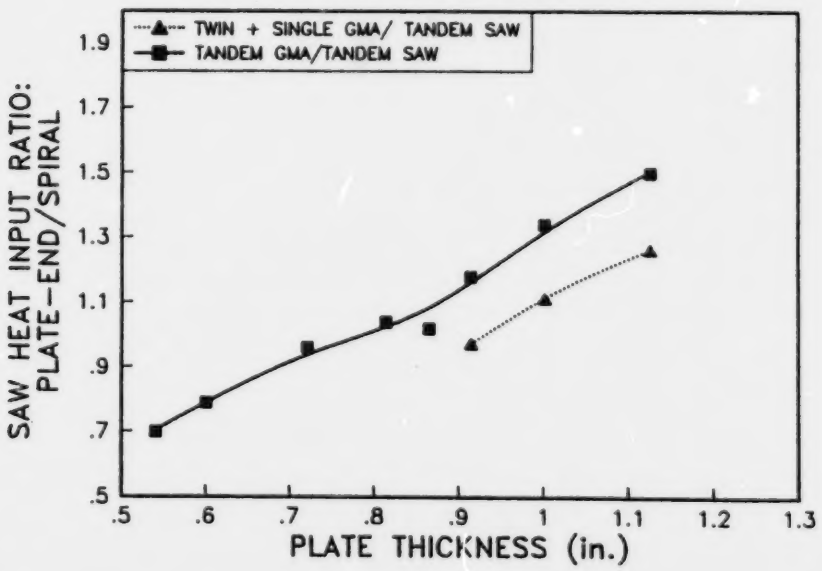
Typically 0.864in thick plate is welded at 157 kJ/in with the arc fusion depth at 33 percent and the bevel depth at 51 percent for a total penetration of 84 percent (Figure 19).

Figure 19: Typical Plate-end Weld Formation



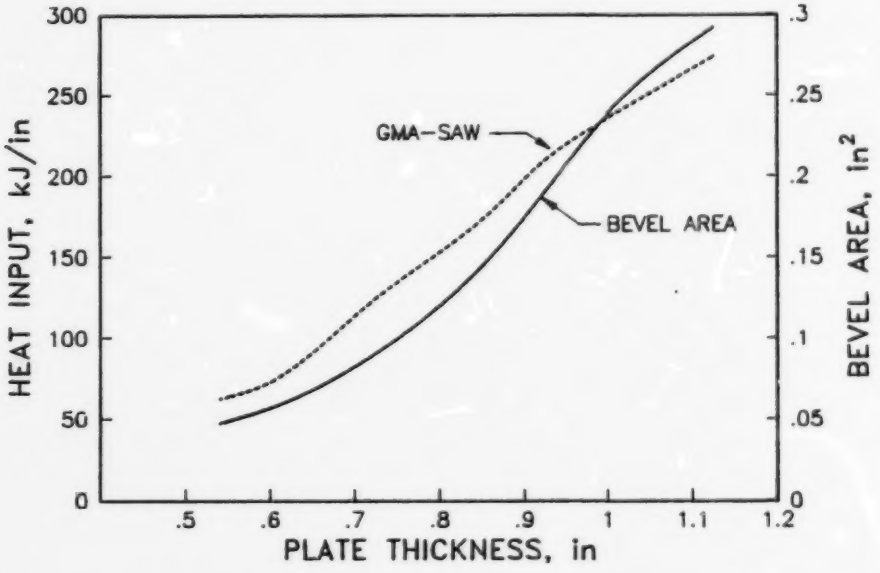
In comparison, the heat input for spiral seam welding is approximately 100 kJ/in, 36 percent less than the plate-end weld reflecting the balance between ID and OD weld bead sizes and penetrations (Figure 20).

Figure 20: SAW Heat Input Comparison between Plate-end and Spiral Welds



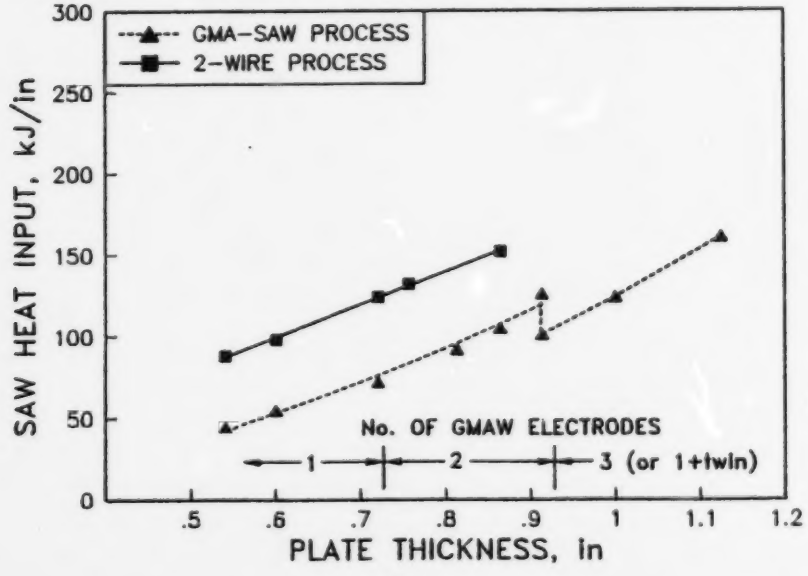
GMA-SAW divides the heat input between its component processes, forming separate weld beads. The result is significant changes to the welding procedure for 0.864in thick plate. Since the GMAW arc fusion depth is 42 percent less than that produced by the two-wire SAW procedure, the bevel depth must be increased by 39 percent, from 0.433in to 0.600in, to reach the 85 percent penetration objective. As a result, the bevel area increases by 92 percent (Figure 21).

Figure 21: GMA-SAW Procedures



The weld metal deposited by the GMAW head(s) helps to offset the large increase in heat input required to fill the bevel. When preceded by two 0.096in diameter GMAW electrodes, the SAW component heat input is reduced by 20 percent compared to two-wire SAW (Figure 22).

Figure 22: Plate-end Weld SAW Heat Input



GMA-SAW procedure predictions from 0.540in to 1.125in thick plate suggest that the roots of the plate-end and the OD completion SAW beads will overlap and no GMAW deposited metal will remain in the cross seam weld (see Appendix 4).

GMA-SAW Weld Mechanical Properties

Weld mechanical properties are adversely affected by the high heat inputs and slow weld cooling rates that are involved in plate-end welding thick skelp. The resulting HAZ grain is coarsened and the fusion zone is comprised of brittle microstructures which increase strength and hardness while decreasing ductility and toughness. Since GMA-SAW reduces the SAW heat input, improved weld mechanical properties are expected.

No significant differences in weld metal and HAZ mechanical properties were found between plate-end welds produced by GMA-SAW or two-wire SAW. Better weld and HAZ mechanical properties may result from improved skelp composition (reduced Mn and Mo plus a Ti addition). This area requires further study, but does not prevent the commercialization of the GMA-SAW process.

We made two series of cross seam welds using both GMA-SAW and two-wire SAW for plate-end welding followed by single-wire DC SAW to complete the joint from the other side. The first series welded 0.835in thick plate using single-wire GMA/two-wire SAW (1GMA-2SAW) and the second series welded 0.920in plate using two-wire GMA/two-wire SAW (2GMA-2SAW). The details are contained in Appendix 3.

1. GMA HAZ Hardness

The HAZ of the plate-end weld contains three distinct coarse-grained microstructures[11] (Table V) which are produced by the thermal cycles each region has undergone (Figures 23-26). The microhardness of the HAZ regions varies depending on its microstructure (Table VI), the intercritically reheated region of the plate-end weld HAZ being the hardest.

Table V: Plate-end Weld HAZ Region

HAZ Region	Peak Temperature (°C)	
	1st Cycle	2nd Cycle
E Subcritical	>1350	<500
D Intercritical	>1350	≈700
C Normalized	>1350	≈1000

Table VI: Microhardness of Reheated Regions of Plate-end Weld HAZ

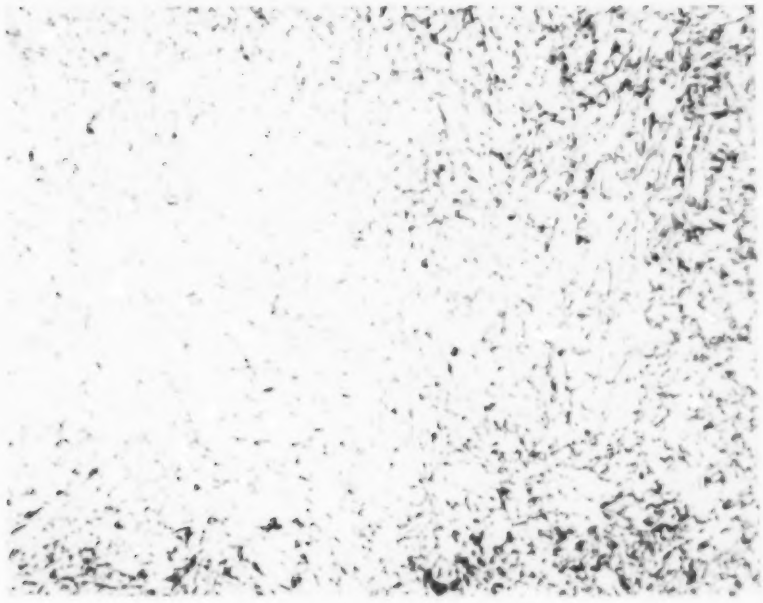
Weld	HAZ Region Microhardness (HV0.5)					
	'E' Subcritical		'D' Intercritical		'C' Normalized	
	Average	Maximum	Average	Maximum	Average	Maximum
2-Wire SAW	239	243	263	267	254	254
2GMA-2SAW	253	265	278	286	268	273

Figure 23: Regions of Plate-end Weld HAZ (7X)

Region E - Subcritical Reheat
Region D - Intercritical Reheat
Region C - Normalized Reheat

Figure 24: Subcritically Reheated Regions ("E") of Plate-end Weld HAZ

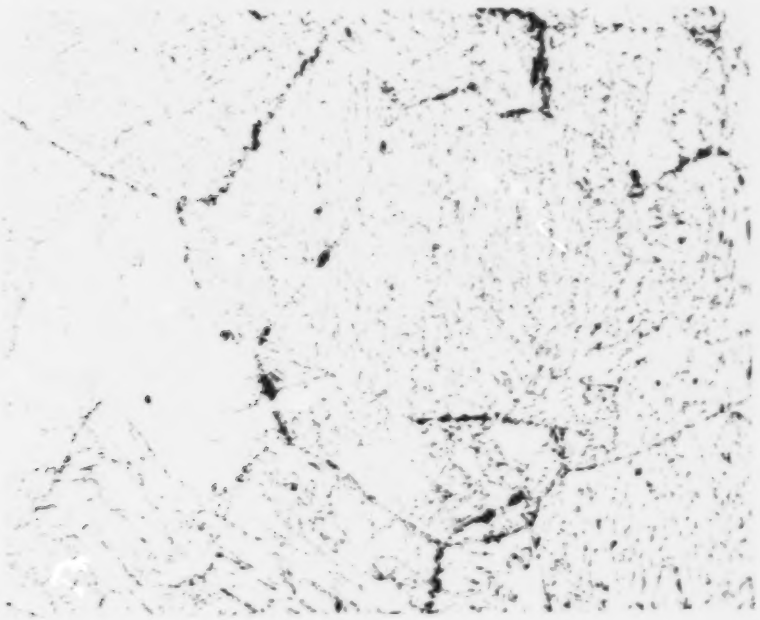
(a) Two-wire SAW (500X)



(b) Two-wire GMA/Two-wire SAW (500X)

Figure 25: Intercritically Reheated Region ("D") of Plate-end Weld HAZ

(a) Two-wire SAW (500X)



(b) Two-wire GMA/Two-wire SAW (500X)

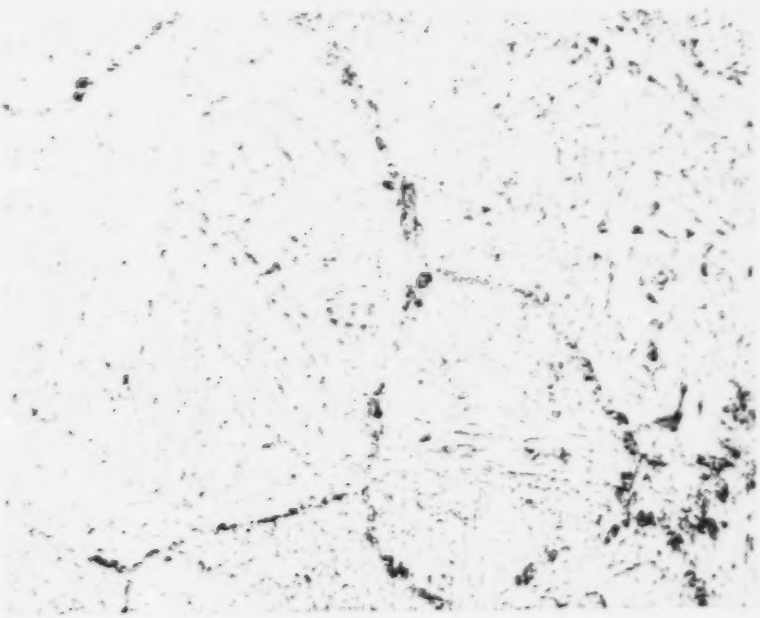
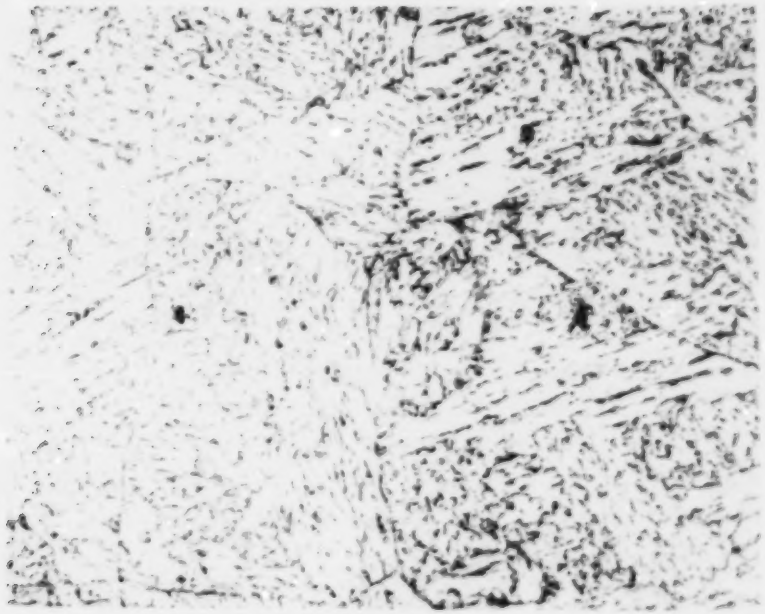
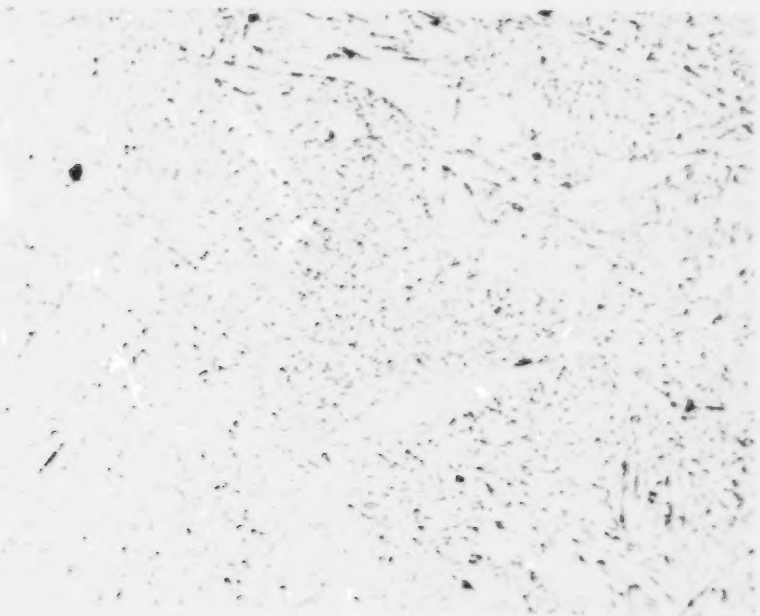


Figure 26: Normalized Region of Reheated ("C") Plate-end Weld HAZ

(a) Two-wire SAW (500X)



(b) Two-wire GMA/Two-wire SAW (500X)



The GMA-SAW procedure produced a slightly harder HAZ in all regions compared to the two-wire procedure. The difference can only be attributed to a reduction in the SAW heat input and perhaps some changes in SAW deposit cooling rate from overwelding hot GMAW deposits. There are no significant differences in grain size between the welds; therefore, the hardness difference must be from the microstructure. Further study of heat input versus microstructure is required using contemporary skelp chemistries and refined GMA-SAW operating procedures.

2. GMA-SAW HAZ CTOD Toughness

Transverse weld coupons, BxB (where B = wall thickness) square, were surface notched and fatigue cracked so that the crack tip was located in the subcritical region of the plate-end weld HAZ. Table VII summarizes the CTOD values obtained at a -5°C test temperature.

Table VII: HAZ CTOD and Crack Tip Location*

Weld	CTOD** at -5°C (in)	Crack Tip Location	
		Distance from Fusion Boundary (in)	Depth Below Surface*** (in)
2-Wire SAW	0.0036 0.0021	0.007 0	0.22 0.23
Average	0.0029	0.004	0.23
GMA-SAW	0.0013 0.0013	0.017 0.021	0.24 0.24
Average	0.0013	0.019	0.24

* All crack tips located in the subcritically reheated region of the plate-end weld HAZ.
** Transverse specimen, BxB, surface notched.
*** Bead reinforcement machined off prior to notching specimen.

The skelp composition generated low HAZ toughness for both welds. This material represents Stelco's thick skelp technology in the late-1970s. Since then skelp alloy content, therefore hardenability, has been reduced. Also, titanium has been added to reduce the prior austenite grain size. Both measures improve HAZ toughness for a given thermal history.

The HAZ CTOD toughness values are too low to assess the effect of GMA-SAW. The two-wire SAW weld HAZ appears to be tougher and the difference may reflect the higher hardness of the GMA-SAW HAZ in the subcritically reheated region at the crack tip. More extensive work is required using up-to-date skelp compositions to assess the effect of GMA-SAW on HAZ toughness. Presently, the GMA-SAW process does appear to have a major effect on HAZ toughness for plate-end welding.

3. Weld Metal Charpy

Transverse Charpy specimens were machined from the mid-wall position and V-notched on the weld centerline in the through-thickness direction. Figures 27 and 28 compare the transition curves for absorbed energy and percent shear ratings of the fracture faces between the two-wire SAW and GMA-SAW welds. There is no significant difference in the Charpy toughness.

Figure 27: Weld Metal Charpy Energy Transition

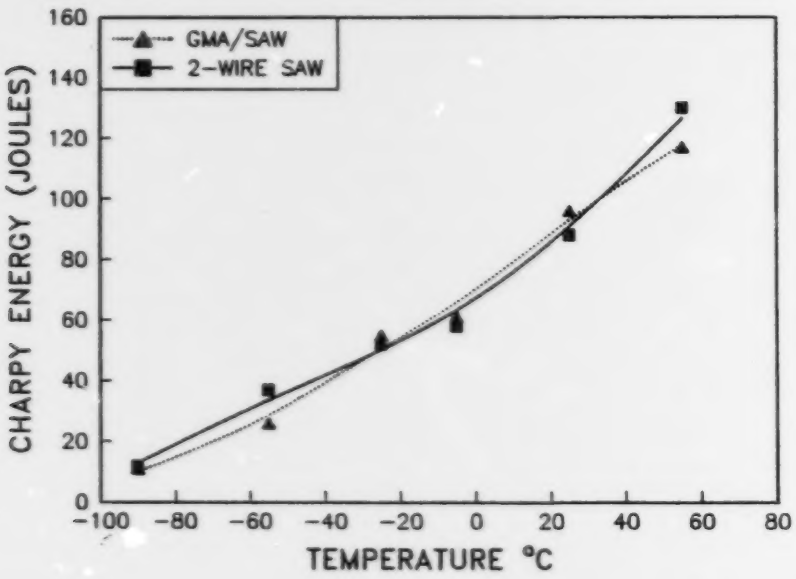
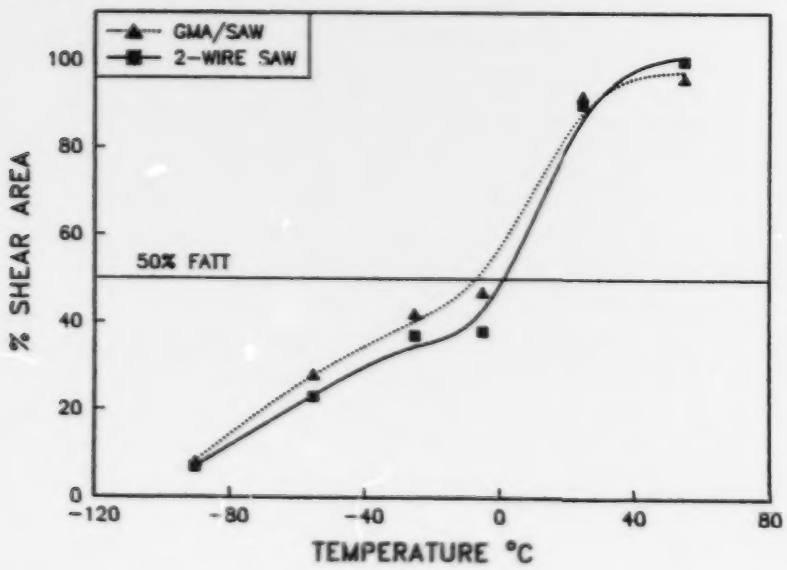


Figure 28: Weld Metal Charpy Shear Transition



4. GMA-SAW Weld Metal Strength

The strength of the plate-end weld metal depends on its chemical composition for a given heat input and cooling rate. Table VIII summarizes the all-weld-metal tensile properties. There is no effect on strength from process configuration.

Table VIII: Weld Metal Strength*

Process Configuration	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	% Elongation (over 1in Gauge Length)
Single Wire GMA/SAW:			
• Plate-end Weld	90	105	21
• Cross weld	95	109	23
Two-wire GMA/SAW:			
• Cross Weld	91	103	12

* All weld metal Hounsfield specimens.

5. GMA-SAW Weld Metal Hardness

Table IX summarizes the hardness in virgin OD completion weld metal and subcritically reheated plate-end weld metal.

Table IX: Weld Metal Hardness

Weld/Process	Microhardness (HV0.5)	
	Average	Maximum
Plate-end:		
• 2-Wire SAW	255	261
• GMA-SAW	256	258
OD Completion:		
• 2-Wire SAW	246	250
• GMA-SAW	251	256

There is no significant difference in the GMA-SAW versus two-wire SAW deposition hardness as well as chemical compositions (Table V A3).

6. Summary

There were no significant differences in the weld metal and HAZ mechanical properties between plate-end welds that were produced by GMA-SAW or two-wire SAW. This result likely occurred because the SAW heat input reduction using GMA-SAW was not enough to improve the microstructure, therefore weld properties, in the skelp composition under study. With an improved skelp composition (reduced Mn and Mo plus a Ti addition) and/or further reductions in the SAW portion of the GMA-SAW heat input, better weld and HAZ mechanical properties may result. This area requires further laboratory study, but does not present a barrier to industrially applying the GMA-SAW process.

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APPENDIX 1

LABORATORY WELDING STATIONS

GMAW Station at WIC

The GMAW station at WIC was built using a side-beam frame with a motor driven face plate. The welding head, wire feed control and 65 lb electrode wire coil were mounted on the face plate. A steel table was positioned under the side-beam frame so that the welding head setup traversed down the length of a test plate that was clamped to the table's surface. Welding power was supplied by an ESAB 1000A DC rectifier with a constant voltage volt-ampere characteristic curve design and used in conjunction with an ESAB A-6 wire feed controller. A second power supply-wire feed controller combination was used for preliminary tests of tandem two-wire GMAW. Table I A1 summarizes the welding equipment details.

Table I A1: WIC GMAW Station Welding Equipment

Equipment	Manufacturer	Model	Description
DC Power Supply	ESAB	LAD 1000	1000 amp DC Rectifier constant voltage power source 900 A/44 V continuous 1000 A/44 V at 80% duty cycle
Welding Control	ESAB	A-6	This welding control regulates welding current and allows the operator to adjust and set desired current and voltage settings.
Twin Electrode Contact Jaws	ESAB	2659-028-81	This twin wire contact jaw system was used in conjunction with the twin wire tip (Linde).
DC Power Supply (Trail Arc)	Miller	MP65-E	DC rectifier constant voltage power source. It is a semiautomatic system.
Busbar Assembly	Linde	29N19	(see Stelco Welding Lab equipment description)
Wire Feeder	Hobart	MEGA-CON	digital wire feeder which regulates welding current

GMA-SAW Station at Stelco

A four-wire GMA-SAW experimental welding station was built in Stelco's Welding Laboratory that combined two-wire tandem GMAW and two-wire tandem SAW (Figures 1 A1, 2 A1 and 3 A1). The welding heads were mounted on the end of a motor-driven manipulator beam. A steel table was positioned under the boom so the welding heads could traverse down

the length of test coupons clamped to the table. Shielding gas for GMAW was supplied from compressed gas cylinders and regulated by a proportional gas mixer. Electrode wires and a flux supply for SAW was also mounted on the manipulator boom. Table II A1 summarizes the Stelco Welding station equipment details.

Figure 1 A1: Stelco Laboratory GMA-SAW Station

Figure 2 A1: GMA-SAW Welding Head Setup

Figure 3 A1: GMA-SAW System Schematic

	Component List
No.	Description
1A & B	AC Power Supply (Transformer)
2A & B	Welding Control - AC/AC SAW
3A & B	DC Power Supply (Motor Generator)
4A & B	DC Welding Control
5	Proportional Gas Mixer
6	Shielding Gas (Bottles - Argon) (Bottles - CO_2)
7	SAW Welding Tip
8	GMA Welding Tip
9	SAW Flux Hopper
10	GMA Shielding Gas Nozzle

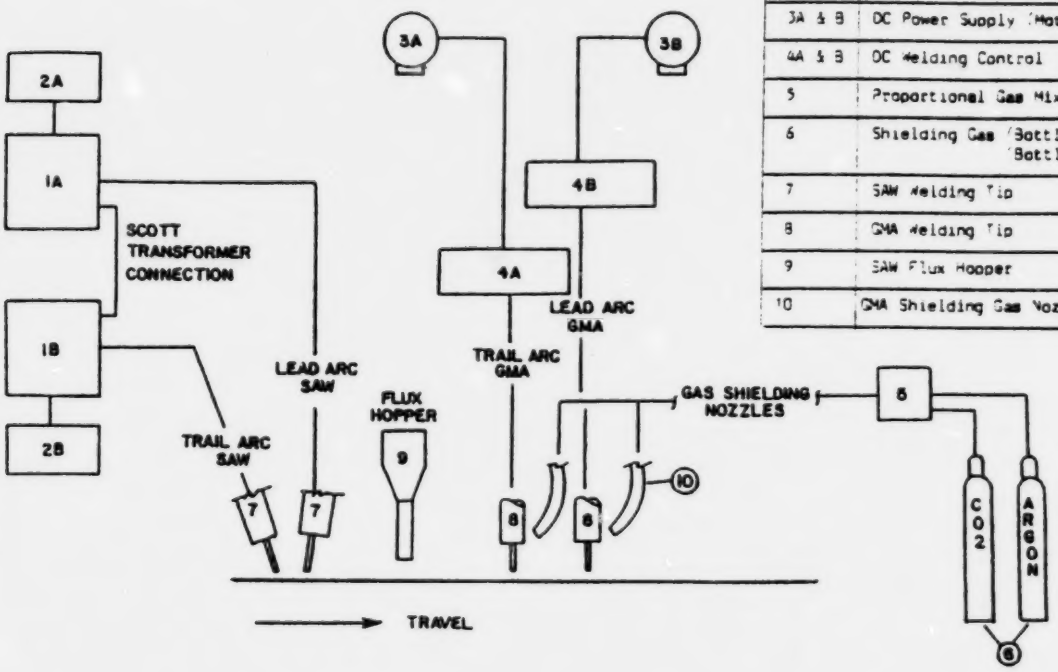


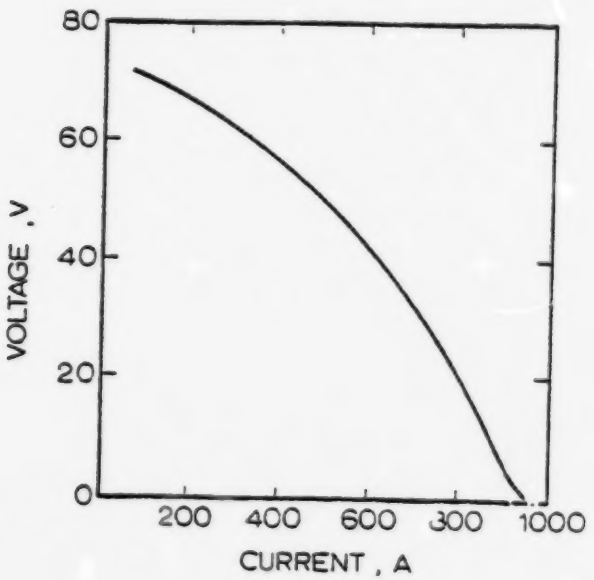
Table II A1: Stelco Welding GMA-SAW Experimental Station Equipment

Equipment	Manufacturer	Model	Description
1 - Proportional Gas Mixer	Smith	239-005	Pressure flow device capable of proportionally mixing two individual gases in variable proportions (±2 percent accuracy).
2 - Busbar Assembly			
• for Saw Head	Linde	29N19	Provides the guidance path for the electrode from the wire straightener to the work piece. The power cables are also attached to the bus bar.
• for GMA Head	(Linde)	29N19	
3 - Wire Feed Assembly			
• for SAW Head	Linde	EH-1	A wire feed motor and gear box which drives the electrode at a rate that is regulated by the control system.
• for GMA Head	Lincoln	NA-3	
4 - SAW Power Supplies Scott-connected	Linde	SA-1000	The two 1000 A transformer power sources are Scott-connected to provide phased welding power.
GMA Power Supplies	Lincoln	SAM 800	A motor generator with a constant current power characteristic.
5 - Welding Controller			
• SAW	Linde	UEC-6	Both are electronic controls that regulate arc voltage by feedback loops.
• GMA	Lincoln	LAF-3	
6 - Welding Tips			
• GMA	Linde	19NA3	- The GMA welding tip used is a one piece solid copper tip with a female connection (Figure 8 A1).
• SAW	Linde	19N49	- The SAW welding tip is a solid copper tip with a carbide insert. This tip has a male connection (Figure 9 A1).

1. GMAW Equipment

Two welding power sources and wire feed control systems were tested. One type used a motor-driven DC generator with a constant current volt-ampere characteristic and wire feed speed regulation by arc voltage feedback. The other type used a motor-driven DC generator with a constant voltage volt-ampere characteristic and wire feed speed regulated by electrode melting rate adjustment via the welding current level. The performance of the latter system became undependable and was replaced by a second GMAW system with a constant current design. In this system a simple voltmeter monitors arc voltage for feedback to the wire feed regulator. Deviations in arc voltage away from the operating setpoint are used to accelerate or decelerate the wire feed motor speed to correct the arc gap length (which is proportional to arc voltage) back to the desired level. The power supply has a constant current or drooping volt-ampere characteristic (Figure 4 A1) so that voltage changes made by the wire feed system cause negligible changes in arc current and current is held constant. The arcs were operated in reverse polarity, that is, the electrodes were positive in the electrical circuit to achieve maximum arc energy fusion depth. Welding was performed traveling toward the ground point.

Figure 4 A1: Static Volt-ampere Characteristic for DC Constant Current Power Supply

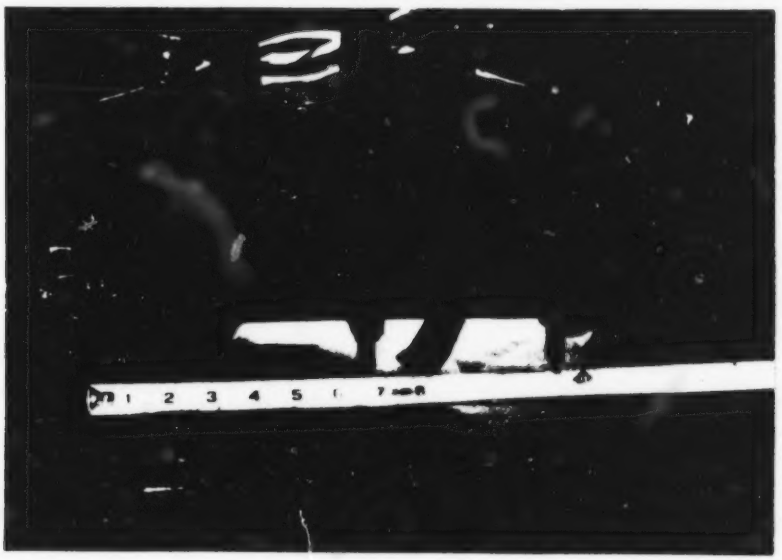


Gases for shielding were piped by flexible hose from pressurized cylinders through a gas mixer into the weld zone. A pressure-flow device proportionally mixed gases according to their molecular weights to achieve mixture setpoints within ±2 volume percent. The units'

performance was specified as being unaffected by inlet pressure, flow rate or outlet pressure variations when operated within the inlet pressure range of 50 to 100 psig. Gas cylinder regulators were used to maintain inlet pressure to the mixer in the specified range. The delivery system was purged automatically when the welding start relay was activated before the arc was established.

The shielding gas was directed into the weld zone using a side delivery tube. The tube's orifice was positioned near the plate surface ahead of the arc (Figure 5 A1). The gas flow rates were adjusted to exclude atmosphere from the arc and weld pool by flooding the region without causing excessive turbulence.

Figure 5 A1: GMA-SAW Head Setup

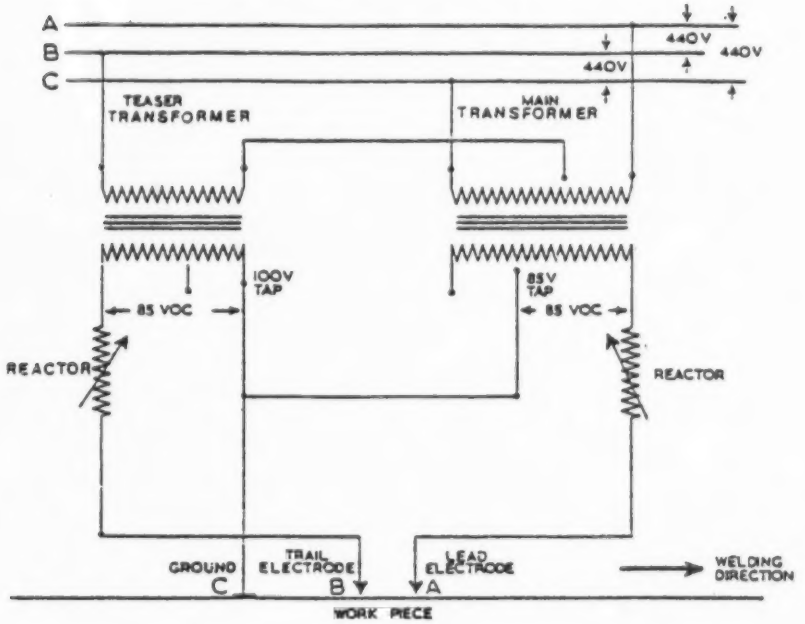


2. SAW Welding Equipment

The AC/AC tandem, Scott-connected, SAW process is designed for two "in-line" electrodes, each electrode powered by a single AC phase. A complete welding system is required for each electrode and it is only in the transformer connection, whereby each electrode receives one phase from the normal three-phase power input, that the systems are integrated. Powering the electrodes in this manner permits control of the current and voltage phasing between the arcs to minimize magnetic field interactions. Hence, good control of weld shape and penetration is achieved at high welding speeds. This system also simplifies the operation of two welding heads to the point where they can be readily handled by an operator who is only qualified to use single wire equipment in pipe manufacture.

Scott-connection of the two transformers, illustrated in Figure 6 A1, provides single-phase power to each electrode. Practically any commercial transformer can be used providing one transformer has a center tap.

Figure 6 A1: Transformer Connections for Scott-tandem Welding[12,13]



The primary of the tapped, or main transformer, is connected across two legs of the three-phase line. The primary of the teaser transformer is connected to the center tap of the main transformer and the third leg of the three-phase line. Secondary connections to the welding wires are preferably made to the 85-volt tap on the main transformer and to the 100-volt tap on the teaser transformer. These preferred connections provide approximately 85 volts on each leg and help to balance the line loads. Welding operation will not be adversely affected if transformers with tapped secondaries are not available. The teaser transformer can be used up to its normal rating. The main transformer can be used up to 85 percent rating, since its primary connections will be carrying approximately 15 percent more current than in normal use due to the teaser current. If the main transformer has a 100-volt tap which is not being used, it can be used up to its full rating. The preferred phase rotation at the welding zone is lead, trail, ground or normal clockwise rotation.[12,13]

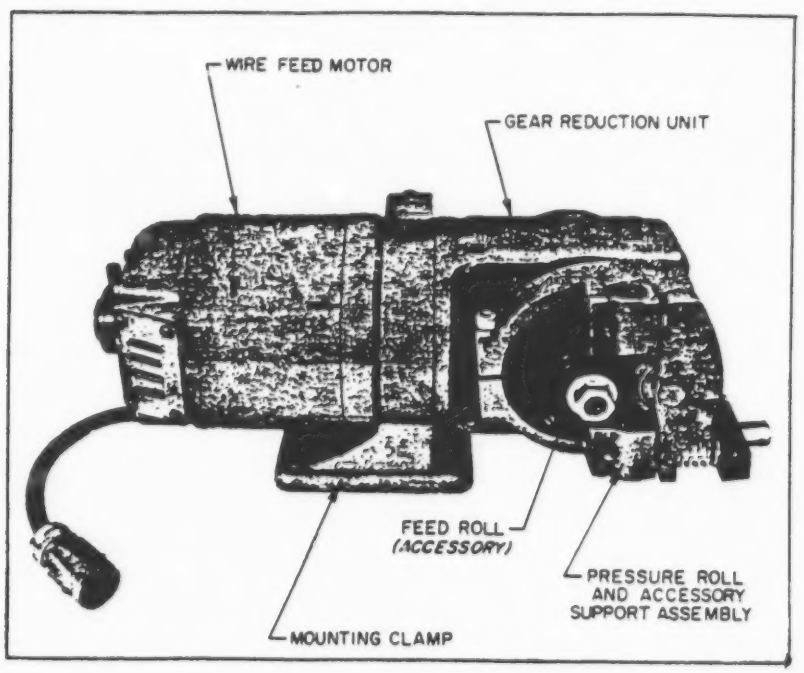
The Laboratory tandem, Scott-connected welding system, for each head, comprises a Linde 1000A transformer, UEC-6 control panel with solid state voltage governor, EH-1 wire feed motor and clapper assembly, plus various Linde bus bar and contact nozzle assemblies. The transformer

connection provides clockwise phase rotation at the heads (i.e., lead, trail, ground) with a 90° voltage phase angle between the lead and trail arcs. A voltage feedback system housed in the UEC-6 panel provides the actual welding control while the transformers maintain an essentially constant welding current. The solid state governing circuit senses arc voltage fluctuations and accordingly adjusts the speed of the wire feed motor to return the arc length (voltage) to the voltage set by the operator. Response time of the control circuit is virtually instantaneous, but ±60 A (±8 percent) and ±2.5 V (±8 percent) fluctuations were normally experienced during the trials.

The SAW system used a Linde EH-1 wire feeder (Figure 7 A1) as the basic drive mechanism to pull electrode wire from the supply reel and push it through the bus bar and contact assembly. This feeder is a rugged, high torque unit designed for heavy duty industrial application. It is composed of five basic units, viz:

- the shunt-wound 1/4 hp, 220 V motor,
- gear reduction unit,
- pressure roll and bus bar support assembly,
- feed roll, and
- mounting clamp.

Figure 7 A1: Linde EH-1 Wire Feed Assembly



The gear reduction unit contained gearing for a maximum 17 rpm feed roll output which made it capable of feeding 5/32in diameter electrode wire at arc current levels between 500 and 1100 A.

The bus bar and contact nozzle designs were similar for both the GMAW and SAW heads (Figures 8 A1 and 9 A1). They are both constructed of thick copper parts to minimize resistive heating and aid in dissipating the heat without softening and distortion. The equipment differed mainly in the design of the contact tip; the SAW tip being more massive. Transfer of electricity from the bus bar to the electrode relies on sliding contact as the wire passes through the tip. The sliding contact wears the tip passage so that the tip must be replaced otherwise poor electrical contact leading to welding defects results.

Figure 8 A1: GMA Bus Bar/Shielding Gas Nozzle Assembly

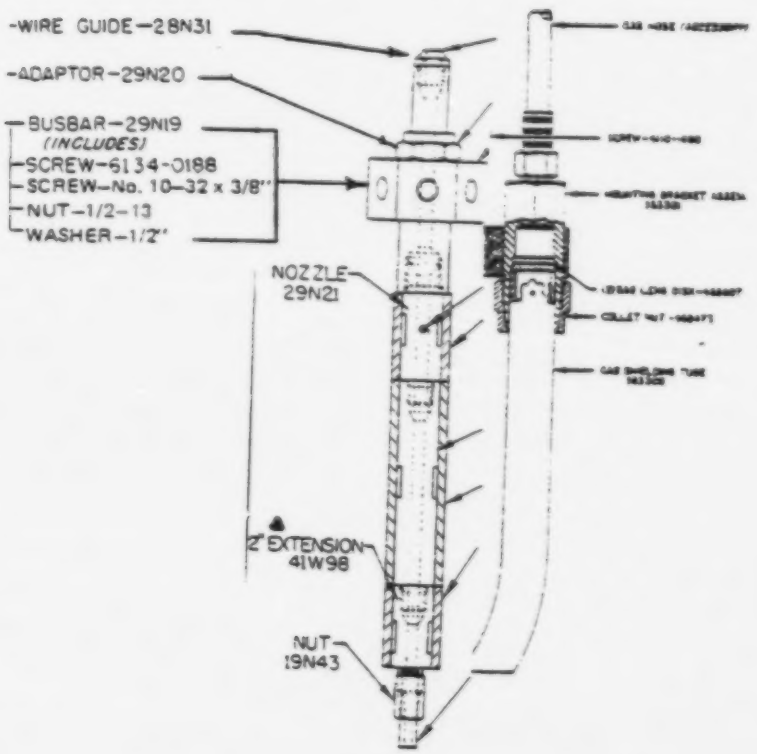
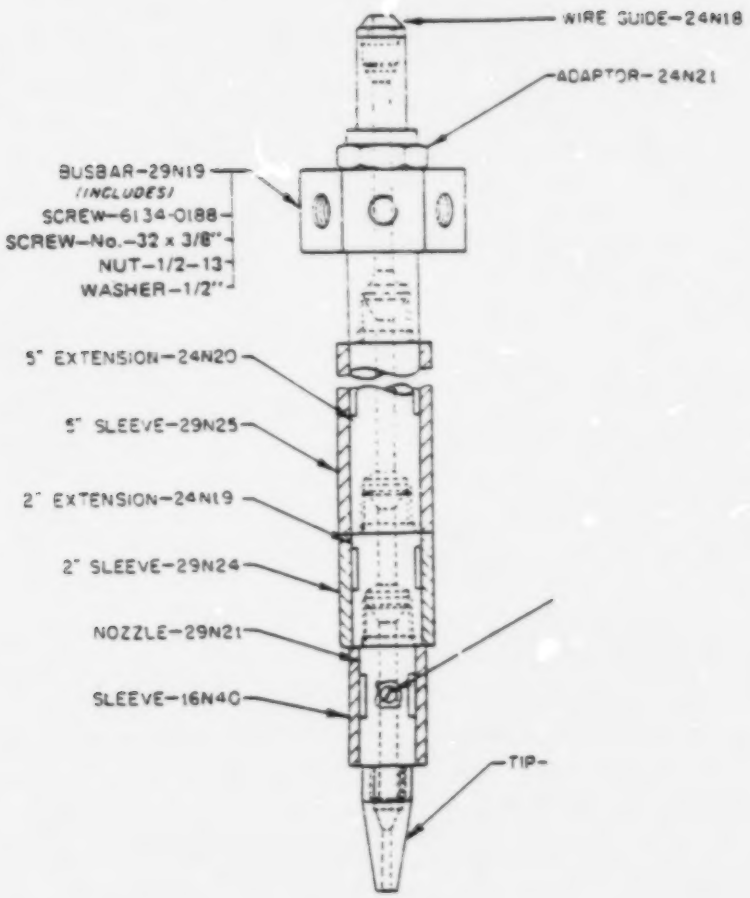


Figure 9 A1: SAW Bus Bar Assembly



The Linde UEC-6 wire feed controller uses arc voltage feedback to regulate wire feed speed. Essentially, the system operates the same as in constant current GMAW except that the controller design is much more sophisticated because welding is performed with AC rather than DC power.

Flux System

SAW flux is contained in a hopper having a cone shape bottom. This hopper is situated above the bus bar and is gravity fed ahead of the lead arc of the submerged-arc system.

APPENDIX 2

GMAW OPERATING PROCEDURE LOBES

Table I A2: GMAW Operating Lobe for 0.096in diameter Electrode, 75% CO_2/25% A at 25 in/min in Bead-on-plate Tests with Constant Potential Regulation

Weld Identification No.	Current (A)	Voltage (V)	Acceptance Criteria: Arc Stability	Spatter Level	Quality: Internal	Quality: External	Total Rating
19	450	26	5	1	1	1	8
20	600	26	3	1	1	1	6
21	525	28	5	5	5	5	20
22	600	30	5	1	3	3	12
23	675	32	1	1	1	1	4
24	450	32	5	5	5	5	20
25	675	36	3	1	1	1	6
26	525	30	5	5	5	5	20
27	450	28	5	5	5	5	20
28	600	32	3	3	3	3	12
29	525	26	1	1	1	1	4
30	600	28	3	1	3	1	8
31	450	30	5	5	5	5	20
32	525	32	5	5	5	5	20
33	675	30	3	1	1	1	6
34	450	34	5	5	5	5	20
35	525	34	5	5	5	5	20
36	600	34	3	5	5	3	16
37	675	34	1	1	1	1	4
38	450	36	5	5	5	3	18
39	525	36	5	5	5	5	20
40	600	36	3	5	5	5	18
41	675	36	3	1	1	1	6
42	450	38	3	3	3	3	12
43	600	38	5	3	3	3	14
44	675	38	3	3	3	3	12
45	750	38	1	1	1	1	4
46	700	38	1	1	1	1	4
47	375	26	1	1	1	1	4
48	375	32	1	1	1	1	4
49	375	28	3	1	3	3	10
50	375	34	1	1	1	1	4

Total Rating - 4 to 8 Unacceptable
10 to 14 Marginal
15 to 20 Acceptable

Table II A2: GMAW Operating Lobe for 0.096in diameter Electrode, 75% CO_2/25% A at 25 in/min in Bead-on-plate Tests with Constant Current Regulation

Weld Identification No.	Current (A)	Voltage (V)	Acceptance Criteria: Arc Stability	Spatter Level	Quality: Internal	Quality: External	Total Rating
52	450	26	3	1	5	3	12
53	450	28	5	5	5	5	20
54	450	30	5	5	5	5	20
55	450	32	5	5	5	5	20
56	450	34	5	5	5	5	20
57	450	36	5	3	3	3	14
58	450	38	5	1	5	3	14
59	525	36	5	5	5	5	20
60	525	34	5	5	5	5	20
61	525	32	5	5	5	5	20
62	525	30	5	5	5	5	20
63	525	28	3	1	3	3	10
64	525	26	1	1	1	1	4
65	375	26	1	1	1	1	4
66	375	28	3	3	3	1	10
67	375	30	3	1	3	1	8
68	375	32	3	1	3	1	8
69	375	34	3	1	1	1	6
70	375	36	1	1	1	1	4
71	600	36	5	5	5	5	20
72	600	34	5	5	5	5	20
73	600	32	5	5	5	5	20
74	600	30	5	5	5	5	20
75	600	28	3	1	1	1	6
76	600	38	5	5	5	5	20
77	525	38	5	5	5	5	20
78	525	40	5	3	3	3	14
79	600	40	5	3	3	3	14
80	675	30	3	1	1	1	6
81	675	34	1	1	1	1	4
92	675	38	3	1	1	1	6

Total Rating - 4 to 8 Unacceptable
10 to 14 Marginal
15 to 20 Acceptable

Table III A2: GMAW Operating Lobe for 0.125in diameter Electrode, 75% CO_2/25% A at 25 in/min in Bead-on-plate Tests with Constant Potential Regulation

Weld Identification	Current	Voltage	Acceptance Criteria				Total Rating
			Arc Stability	Spatter Level	Quality		
No.	(A)	(V)			Internal	External	
83	600	28	5	3	5	5	18
84	600	30	5	5	5	5	20
85	600	32	5	5	5	5	20
86	600	34	5	5	5	5	20
87	600	36	3	3	5	3	14
88	600	26	1	1	1	1	4
89	700	30	3	3	3	3	12
90	700	32	3	3	3	1	10
91	700	34	5	5	5	5	20
92	700	36	5	5	5	5	20
93	700	38	5	3	3	3	14
94	700	28	3	1	1	1	6
95	600	38	3	3	3	3	12
96	600	36	3	3	5	3	14
97	600	40	1	1	1	1	4
98	800	30	1	1	1	1	4
99	800	34	1	1	1	1	4
100	800	26	1	1	1	1	4
101	500	30	5	5	5	5	20
103	500	34	3	3	3	3	12
104	500	32	5	5	5	5	20
105	500	28	5	5	5	5	20
106	500	26	3	1	3	3	10
107	500	34	3	3	3	3	12
108	500	36	1	1	1	1	4

Total Rating - 4 to 8 Unacceptable
10 to 14 Marginal
15 to 20 Acceptable

Table IV A2: GMAW Operating Lobe for the Lead Arc in a 2-wire Tandem System with the Trail Arc Held at 525 A, 32 V (0.096in dia electrodes, 75% CO_2/25% A, in Bead-on-plate Tests at 25in/min)

Weld Identification No.	Current (A)	Voltage (V)	Acceptance Criteria				Total Rating
			Arc Stability	Spatter Level	Quality		
					Internal	External	
A-1	450	28	5	5	5	5	20
A-2	450	30	5	5	5	5	20
A-3	450	32	5	5	5	5	20
A-4	450	34	5	5	5	5	20
A-5	450	36	3	3	5	5	16
A-6	500	28	5	5	5	5	20
A-7	500	30	5	5	5	5	20
A-8	500	32	5	5	5	5	20
A-9	500	34	5	5	5	5	20
A-10	500	36	5	5	5	5	20
A-11	550	28	5	5	5	5	20
A-12	550	30	5	5	5	5	20
A-13	550	32	5	5	5	5	20
A-14	550	34	5	5	5	5	20
A-15	550	36	5	5	5	5	20
A-16	650	28	1	1	1	1	4
A-17	600	28	1	1	1	1	4
A-18	600	32	3	3	3	3	12
A-19	600	36	3	3	3	3	12
A-20	550	38	1	1	1	1	4
B-1	450	28	5	5	5	5	20
B-2	450	32	5	5	5	5	20
B-3	450	36	3	3	5	3	14
B-4	550	28	5	5	5	5	20
B-5	550	32	5	5	5	5	20
B-6	550	36	5	5	5	5	20
B-7	550	38	3	3	5	3	14
B-8	550	40	3	3	3	3	12
B-9	600	28	1	1	1	1	4
B-10	600	36	5	3	5	5	18
B-11	600	40	3	3	3	1	10
B-12	600	32	3	1	3	1	8
B-13	600	38	1	1	1	1	4
B-14	500	38	3	1	3	3	10

Total Rating - 4 to 8 Unacceptable
10 to 14 Marginal
15 to 20 Acceptable

Table V A2: Single-wire Groove Welds with 1.6 mm Electrode*

Weld No.	I (A)	S (mm/s)	P (mm)	Comments
200	300	22	0	no crack
201	300	26	0	no crack
202	300	30	0.055	no crack
203	350	22	0.051	no crack
204	350	26	0.031	no crack
205	350	30	-	cracked
206	400	22	-	cracked
207	400	26	-	cracked
208	400	30	-	cracked
209	300	22	0.038	no crack
210	300	26	0.039	no crack
211	300	30	-	cracked
212	350	22	-	cracked
213	350	26	-	cracked
214	350	30	-	cracked

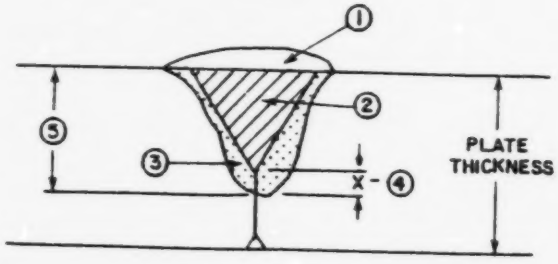
* Welds No. 200 to 208: no gap
Welds No. 209 to 214: 0.8 mm gap

APPENDIX 3

CROSS SEAM WELDING PROCEDURES AND MECHANICAL PROPERTIES

The cross seam joint in Stelform spiral pipe is first prepared in a milling operation with dry carbide cutters then welded in two passes. The plate end is machined square then the top edge is beveled at a 25° angle to a predetermined depth depending on the plate thickness. The corner of the bottom edge is shaved at a 45° angle to a depth between 0.060 and 0.11in also depending on plate thickness. In the first welding operation "plate-end welding" the plate edges are butted (to form a 50° included angle, single V preparation approximately one-half of the plate thickness deep from the top surface (Figure 1 A3) and welded with two-wire, tandem, AC/AC SAW. The penetration of the plate-end weld exceeds 70 percent. After pipe forming the cross seam joint is welded from the other side (now the pipe OD) using single-wire DC SAW so that the weld roots overlap by approximately 15 to 20 percent.

Figure 1 A3: Plate-end Weld Nomenclature



① REINFORCEMENT (CAP)
② BEVEL AREA (JOINT FILL)
③ BASEPLATE FUSED AREA
④ ARC FUSION DEPTH
⑤ PENETRATION (% OF W.T.)

Laboratory cross welding trials using 1GMA-2SAW (Table I A3), 2GMA-2SAW (Table II A3), two-wire SAW (Tables I A3 and II A3) and single-wire SAW (Table II A3) were performed to evaluate and compare weld and HAZ mechanical properties. All SAW was performed with Stelco Grade 80 electrode wire and ESAB 10.71 flux. Typical joint edge preparations are shown in Table III A3. The bead dimensions of a laboratory plate-end weld produced by two-wire SAW, versus GMA-SAW are compared in Table IV A3. All GMAW was performed using 0.096in diameter, Linde 65 electrode wire and 75/25 CO_2/argon shielding gas. The chemical composition of the materials is summarized in Table V A3. Weld metal Charpy data is contained in Table VI A3. CTOD at -5°C is contained in Table VII A3.

Table I A3: Plate-end Welding Procedures for 0.835in Plate

Welding Process	Travel Speed (in/min)	GMAW				SAW								Total Heat Input (kJ/in)	
						Lead Electrode				Trail Electrode					
		Current (A)	Voltage (V)	Electrode Diameter (in)	Heat Input (kJ/in)	Current (A)	Voltage (V)	Diameter (in)	Heat Input (kJ/in)	Current (A)	Voltage (V)	Diameter (in)	Heat Input (kJ/in)	SAW	GMA-SAW
2-wire SAW	22	-	-	-	-	900	33	0.156	81	750	37	0.156	76	157	-
1GMA-2SAW	25	600	30	0.096	43	750	33	0.156	59	700	37	0.156	62	121	164

Table II A3: Cross Weld Procedures of 0.920in Thick Plate

Weld Pass	Process	Travel Speed (in/min)	Lead Arc					Trail Arc					Heat Input (kJ/in)
			Wire Dia (in)	Current (A)	Voltage (V)	Tip Angle (°)	Stand-off (in)	Wire Dia (in)	Current (A)	Voltage (V)	Tip Angle (°)	Stand-off (in)	
Plate-end	two-wire SAW (AC)	22	5/32	820-860	32-34	7 trailing	1	5/32	840-860	36-38	7 leading	1	159.0
OD Completion	one-wire SAW (DC)	25	5/32	750-770	35-37	0	3/4	-	-	-	-	-	65.7
Plate-end (GMA-SAW)	two-wire GMAW	25	3/32	550-570	32-33	0	3/4	3/32	525-550	32-33	0	3/4	82.5
	two-wire SAW (AC)	25	5/32	740-760	32-34	7 trailing	1	5/32	780-820	36-38	7 leading	1	126.7
OD	one-wire SAW (DC)	25	5/32	750-770	35-37	0	3/4	-	-	-	-	-	65.7

[a] GMAW electrode spacing = 5.5in (measured on the plate surface between the electrode inside surfaces)
GMAW-SAW electrode spacing = 5.5in (as above)
SAW electrode spacing = 0.5in (as above)

Table III A3: Cross Weld Joint Designs for 0.864in Thick Plate

Plate-end Welding Process	Bevel Depth (in)		Land Thickness (in)	Bevel Area (in^2)		Bevel Angle (°)	
	Plate-end	OD Completion		Plate-end	OD Completion	Plate-end	OD Completion
two-wire SAW	0.433	0.150	0.312	0.087	0.014	25 (50 included)	45 (90 included)
1GMA-2SAW	0.600	0.050	0.250	0.167	0.0025	25 (50 included)	45 (90 included)

Table IV A3: Bead Dimensions in 0.920in Thick Plate

Plate-end Welding Process	Electrode Deposited Area (in^2)*				Total Deposited Area (in^2)	Fusion Depth (in)	Penetration (%)	Bead Reinforcement	
	SAW		GMAW					Height (in)	Width (in)
	Lead	Trail	Lead	Trail					
Two-wire SAW	0.070	0.077	-	-	0.147	0.214	75	0.143	0.980
2GMA-2SAW	0.054	0.064	0.039	0.037	0.181	0.200	86	0.076	1.080

* calculated using WIC weld modeling program

Table V A3: Chemical Analysis (Wt %)

Material	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb	ASA	Ti	N	O_2
Plate:															
0.920in WT	0.07	2.11	0.007	0.006	0.26	0.04	0.25	0.03	0.56	0.002	0.06	0.010	0.002	0.011	-
0.835in WT	0.05	2.12	0.006	0.005	0.25	0.03	0.24	0.03	0.54	0.010	0.06	0.014	0.002	0.008	-
Wire:															
Linde 65*	0.04	1.20	0.017	0.020	0.50	-	-	-	-	-	-	0.100	0.100	-	-
Stelco 80	0.07	1.88	0.005	0.011	0.31	0.02	0.26	0.02	0.49	0.005	-	0.018	0.111	-	-
Weld Metal:															
1GMA-2SAW in 0.835in plate	0.07	1.93	0.007	0.006	0.08	0.03	0.28	0.03	0.40	0.003	0.08	0.042	-	0.007	-
2GMA-2SAW in 0.920in plate	0.07	1.89	0.011	0.010	0.33	0.06	0.21	0.04	0.43	0.003	0.03	0.009	0.015	0.015	0.039
2-wire SAW in 0.835in plate	0.06	1.92	0.007	0.008	0.07	0.03	0.29	0.03	0.45	0.003	0.08	0.049	-	0.005	-
2-wire SAW in 0.920in plate	0.07	1.94	0.009	0.008	0.31	0.06	0.25	0.03	0.52	0.003	0.04	0.008	0.018	0.012	0.033

* Zr = 0.07 wt %

Table VI A3: Cross Weld Metal Charpy Transitions*

Plate-end Welding Process	Plate Thickness (in)	Code No.	Temperature (°C)	Energy (J)				Shear Area (%)			
				1	2	3	Average	1	2	3	Average
2-wire SAW	0.920	C11	+55	130	123	136	130	100	100	100	100
			+25	80	88	96	88	90	85	95	90
			-5	63	105**	53	58	40	75**	35	38
			-25	42	63	51	52	35	40	35	37
			-55	46	18	47	37	30	20	20	23
			-90	7	18	10	12	5	10	5	7
	0.835	C1	-5	114	105	124	114	-	-	-	
2GMA-2SAW	0.920	C5	+55	116	118	116	117	96	97	96	96
			+25	97	94	96	96	95	90	90	92
			-5	56	49	77	61	45	45	50	47
			-25	52	64	49	55	40	45	40	42
			-55	25	21	32	26	30	25	30	28
			-90	8	11	13	11	7	7	10	8
1GMA-2SAW	0.835	A1	-5	68	84	76	76	-	-	-	-
		A3	-5	96	93	91	93	-	-	-	-

* transverse, full size specimens machined from the mid-wall and notched through-thickness on the weld centerline.
** excluded as outlier.

Table VII A3: Weld Metal[a] and HAZ[b] CTOD (at -5°C)

Test No.	Material	HAZ Notch Distance** from Fusion Boundary (in)	CTOD (in)	Comments
C-11-1	2-wire SAW Weld Metal	-	0.0079	
C-11-2	"	-	0.0062*	
C-11-3	"	-	0.0081*	
C-11-4	"	-	0.0072*	
C-11-5	"	-	0.0135*	
C-7-1	CMA-SAW Weld Metal	-	0.0072*	
C-7-2	"	-	0.0085*	
C-7-3	"	-	0.0070*	
C-7-4	"	-	0.0029*	
C-7-5	"	-	0.0050*	First pop-in: Max load at 0.0078in
C-11-6	2-wire SAW HAZ	in weld metal	0.0014	
C-11-7	"	0.007	0.0036	
C-11-8	"	0	0.0021	
C-11-9	"	in weld metal	0.0035	
C-11-10	"	0.013	0.0011	First pop-in: Max load at 0.0076in
C-7-7	CMA-SAW HAZ	0	0.0080	
C-7-8	"	0.016	0.0013	
C-7-9	"	0.020	0.0008	First pop-in: Max load at 0.0037in
C-7-10	"	0.021	0.0013	

* Test results considered invalid due to >5 percent crack front curvature (BS 5762.1979). No specimen pre-compression.

** Measured at coupon mid-section.

(a) Specimen dimensions t x 2t, notched through-wall on weld centerline.

(b) Specimen dimensions t x t, surface notched (with reinforcement removed) into subcritically reheated region of HAZ (aiming for coarse grained area).

APPENDIX 4

PREDICTING GMA-SAW PROCEDURES AND BEAD FORMATION

GMA-SAW Process Model

Empirical equations that relate operating parameters to bead formation were selected from the literature and used to computer model GMA-SAW bead formation. The program inputs are joint design details and "best guess" welding parameters and the output is weld metal deposition area, bead reinforcement area, heat input and estimated reinforcement height. The welding procedure inputs are refined by evaluating the program output, correcting the input procedures, reevaluating the output then performing as many iterations as required to obtain the most desirable bead shape predictions.

The model has two limitations. It does not predict the depth of arc fusion therefore cannot predict the location of the weld root. The GMAW fusion depth is the key factor determining the bevel depth to achieve 85 percent plate-end weld penetration. Based on the experienced gained in this project, the GMAW fusion depth can be estimated and the bevel depth specified for the model. The second weakness is that the model estimates the weld bead reinforcement shape based on the equation of an ellipse with its major axis equal to the joint opening at the top surface of the plate. This is a poor simulation but one that can be modified and improved to better represent the actual bead reinforcement. The axis length in the ellipse equation can be factored (based on actual weld profiles) to give a realistic bead reinforcement height as well as width.

The model predictions can be improved by using more accurate empirical equations for electrode melting rate. Experimental results (with coefficient of multiple correlation > 0.99) reported by Chandel[14,15] show that separate equations (1 to 3 below) are required to predict electrode melting rates for AC versus DCRP SAW welding. Also, Lesnewich[16] notes that electrode melting rates differ for GMA versus SAW (equation 4 below).

1. Submerged-arc Electrode Melting Rate Equations

$$1 - MR \text{ (for AC)} = 0.01523 \times I + 1.6882 \times 10^{-6} \frac{I^2 L}{d^2} - 2.396$$

$$(R = 0.991)$$

$$2 - MR \text{ (for DCSP)} = 0.016178 \times I + 2.087 \times 10^{-6} \frac{I^2 L}{d^2} - 0.643$$

$$(R = 0.993)$$

$$3 - MR \text{ (for DCRP)} = 0.1037 \times I + 2.2426 \times 10^{-6} \frac{I^2 L}{d^2} - 0.462$$

$$(R = 0.993)$$

where: MR = melting rate (lb/h)
I = current (A)
L = electrode stickout (in)
d = electrode diameter (in)

R is the coefficient of multiple correlation

2. GMAW Electrode Melting Rate Equation

$$4 - MRP = (0.017 + 0.37A) I + \frac{3.69 \times 10^{-8}}{A^{1.26}} I^2 L$$

where: MRP = melting rate for reverse polarity (lb/h)
I = welding current (A)
L = electrode stickout (in)
A = cross-sectional area of the wire

The prediction accuracy of the model would be improved by incorporating these melting rate equations. In addition, model provisions for using one, two, three or twin GMAW electrodes and varying bevel angles would improve its usefulness.

Model Predictions

Table I A4 summarizes the welding procedures and bead formation predictions developed from the model.

Table I A4: GMA-SAW Model Predictions of Plate-end Welding Procedures

GMAW Electrode Configuration	Plate Thickness (in	Bevel Design			GMA Welding						SAW Welding								Welding Speed (in/min)	Area of Reinforcement (in^2)	SAW Heat Input Ratio: Plate-end Weld to Spiral Weld (%)
					Lead		Trail		Total		Lead			Trail			Total				
		Groove Angle °	Bevel Depth (in)	Bevel Area (in^2)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Heat Input (kJ/in)	Dep Rate (lb/hr)	Wire Dia (in)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Wire Dia (in)	Heat Input (kJ/in)	Dep Rate (lb/hr)			
Single 3/32in dia	0.540	50	0.33	0.051	500	32	-	-	19	13	1/8	600	32	500	36	1/8	45	46.4	45	0.022	70
	0.600	50	0.34	0.055	500	32	-	-	24	13	5/32	600	32	500	36	5/32	55	42.9	40	0.033	79
Tandem 3/32in dia	0.720	50	0.44	0.091	500	32	500	32	55	25	5/32	650	32	600	36	5/32	72	50.9	35	0.045	96
	0.813	50	0.52	0.126	550	32	500	32	66	28	5/32	800	32	650	36	5/32	92	60.5	32	0.043	104
	0.864	50	0.56	0.148	550	32	500	32	67	28	5/32	850	32	700	36	5/32	105	65.5	30	0.041	102
	0.913	50	0.62	0.179	550	32	525	32	83	29	5/32	850	32	700	36	5/32	126	65.5	25	0.050	118
	1.000	50	0.68	0.251	550	32	525	32	83	29	5/32	950	32	900	36	5/32	150	80.7	25	0.050	
		40	0.68	0.168	550	32	525	32	83	29	5/32	750	32	700	36	5/32	118	60.4	25	0.050	105
	1.125	40	0.79	0.224	550	32	525	32	83	29	5/32	900	32	850	36	5/32	162	75.5	22	0.064	129
		50	0.79	0.288	550	32	525	32	83	29	3/16	1100	32	950	36	3/16	189	87.3	22	0.026	150
Lead 3/32in dia plus Trail-twin 1/16in dia	0.913	50	0.62	0.179	550	32	800	32	112	42	5/32	700	32	550	36	1/8	101	48.2	25	0.044	97
	1.000	50	0.68	0.215	550	32	800	32	111	48	5/32	900	32	750	36	1/8	124	70.4	25	0.060	111
	1.125	50	0.79	0.288	550	32	800	32	113	42	5/32	950	32	800	36	5/32	161	73.8	22	0.033	126
		40	0.79	0.227	550	32	800	32	113	42	5/32	850	32	700	36	5/32	143	65.5	22	0.057	112

A typical model application for 1in thick plate is as follows based on using the following equations to predict the joint design:

1. Bevel Depth Dimension

$$BD = (t - f) \times P$$

where: BD = bevel depth (in)
t = plate thickness (in)
f = GMAW fusion depth (= 0.020in)
P = plate-end weld penetration (= 0.85 t)

BD = 0.680in for t = 1.0in

2. Land Thickness Dimension

$$LD = 0.2 + (t \times 0.05) + 0.03$$

where: LD = land thickness (in)
t = plate thickness (in)
0.2 = GMAW fusion depth (in)
0.05 = allowance for nominal versus actual t
0.03 = max machining tolerance (in)

LD = 0.28in for t = 1.0in

The model prompts the user to input the joint design and welding procedures, i.e.:

groove angle = 50 degrees
groove depth = 0.68in
joint gap = 0in
travel speed = 25in/min

GMAW lead electrode - diameter = 0.094in
- current = 550 A
- voltage = 32 V

GMAW trail electrode - diameter = 0.094in
- current = 525 A
- voltage = 32 V

SAW lead electrode - diameter = 0.156in
- current = 900 A
- voltage = 32 V

SAW trail electrode - diameter = 0.156in
- current = 800 A
- voltage = 36 V

The model output is shown in Figure 1 A4.

Figure 1 A4: Model Procedure and Bead Formation Predictions for 1.0in Thick Plate

Groove Angle = 50 degrees
Groove Depth = 0.68in
Joint Gap = 0in
Area of Groove = 0.215 sq in
Travel Speed = 25 ipm

GMA	Lead	Trail
El Dia	0.09375	0.09375in
Current	550	525 amps
Voltage	32	32 volts

Dep Rate: 240.64 224.34 mm^3/s

Area of 1st GMA Fill = 0.035 sq in
1st GMA At = 0.084 sq in
Heat Input 1st GMA Pass = 42.24 kj/in

Area of 2nd GMA Fill = 0.032 sq in
2nd GMA At = 0.088 sq in
Heat Input 2nd GMA Pass = 40.32 kj/in

SAW	Lead	Trail
El Dia	0.156	0.156in
Current	900	800 amps
Voltage	32	36 volts
Dep Rate	626.14	543.75 mm^3/s

Area of 1st SAW Fill = 0.091 sq in
1st SAW At = 0.18 sq in
Heat Input 1st SAW Pass = 69.12 kj/in

Area of 2nd SAW Fill = 0.079 sq in
2nd SAW At = 0.169 sq in
Heat Input 2nd SAW Pass = 69.12 kj/in

Reinforcement Area = 0.028 sq in
Est Max Reinforcement Ht = 0.05738lin

It calculates a GMAW deposit area of 0.068in^2 or 32 percent of the total joint preparation area (= 0.215in^2). The remaining joint area is filled by the 0.170in^2 of weld metal deposited by the two-wire SAW. The excess deposit (0.028in^2) forms the bead reinforcement with a predicted bead height of 0.057in. We estimate that the SAW fusion depth of the two-wire SAW is 0.51 t and for single-wire SAW completion welding is 0.40 t. Therefore, the plate-end weld penetration is 75.5 percent and the completed cross weld would not contain any of the GMAW fusion zone or HAZ.